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Research Report

Multiple Experimental Approaches to Investigate Oil Transport Mechanism of Piston-liner System

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ABSTRACT Reduction of piston friction should be achieved without an increase of lubricating oil consumption (LOC). Therefore, an understanding of the oil transport mechanisms is crucial to determine the design parameters of a piston ring.

The oil transport phenomenon was investigated using combinations of some unique measuring techniques that were developed, such as a micro data logger system and fluorescence techniques. Two case studies are reported. The first case is LOC under engine braking conditions. Narrowing of the top ring gap clearance has a significant effect on decreasing the LOC. The effect was caused by decreasing the amount of oil on the 2nd land and not by interrupting the oil flow through the gap. The second case is LOC fluctuation under middle engine speed conditions. The LOC fluctuation was synchronized with the change of the 2nd land pressure, which is related to the top ring rotation and 2nd ring axial motion.

The LOC is dependent on the 2nd land pressure level, which is affected by the ring behavior. Control of the land pressure with an appropriate ring design is thus important. Piston ring design parameters, aside from ring tension, can be used to resolve the LOC issue without an increase in piston friction losses.

KEYWORDS Oil Consumption, Oil Transport, Piston, Piston Ring, Fluorescence Method, Data Logger, Ring Behavior, Land Pressure

1. Introduction

To reduce the environmental load from automobiles, friction reduction in the internal combustion engine system has been executed mainly by lowering the viscosity of lubricating oils or decreasing the tensile force of piston rings. However, these design trends have several trade-off effects, such as promotion of wear at many sliding parts and an increase in lubricating oil consumption (LOC).

Toyota Central R&D Labs., Inc. and Toyota groups have developed several measurement techniques such as a radioisotope tracer method for real-time measurement of the LOC and wear,[1-4] or fluorescence methods to measure oil films,[5-9] and investigated such problems of engine tribology by application of these techniques.

These studies clarified the changes in the LOC and wear due to the changes in engine design factors and operating conditions. However, the physical mechanism that causes these changes is still not clear. We consider that the improvement of each measurement technique and combinations of these techniques would make it possible to clarify the unknown physical mechanism.

In this paper, two case studies on LOC phenomena are reported. The case studies use a combination of more than two measurement techniques to investigate the oil transport phenomena around a piston. The first concerns the LOC under engine braking conditions and the second concerns the LOC fluctuation under middle engine speed conditions. In each case study, the oil film behavior, piston land pressures, piston ring movement (in the circumferential or axial direction), and the amount of the LOC were measured using appropriate methods, and the relations among these measurements were investigated in detail.

2. Oil Consumption under Engine Braking Conditions

LOC increases under transient conditions including the engine braking period.[9-11] It is considered that oil is carried on the gas flow from the crank case to the combustion chamber and intake pipe during engine braking conditions. Therefore, it is important to inhibit oil transport under engine braking conditions for a reduction in the LOC.

The effect of changing the piston ring specifications on LOC and the mechanism were investigated with a combination of multiple measurement techniques.

2. 1 Measurement Methods

2. 1. 1 Test Engine

A single-cylinder engine with a transparent cylinder (75.1 mm diameter × 73.5 mm), a piston for a commercial 1.3 L engine, and SAE5W-20 engine oil with a fluorescent dye (coumarin 6) were used for the test. The operating conditions were 1200 rpm without firing, 80°C oil temperature in the oil pan, and 85°C water temperature in the engine head.

2. 1. 2 Two-dimensional Fluorescence Method

A 2D fluorescence method[7] was applied to observe oil film behavior on the moving piston. **Figure 1** shows the oil film measurement system. A xenon flashlight is irradiated onto the oil film between the piston and the transparent cylinder through a blue optical filter at a specified timing. The fluorescence of the oil film induced by the flashlight is observed with a highly sensitive CCD camera through a yellow optical filter, which shields the camera from the irradiation light wavelength. The oil film thickness distribution is obtained quantitatively from the intensity distribution of the fluorescence by image analysis on a PC.

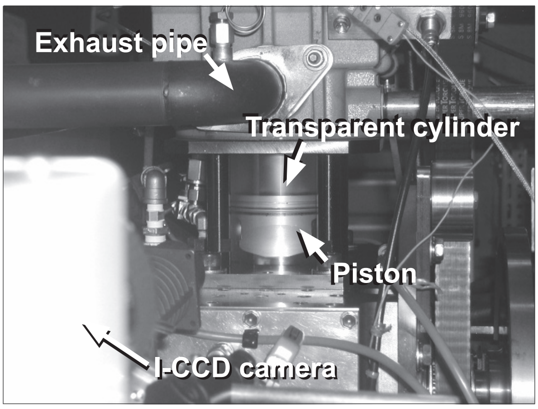
2. 1. 3 Micro Data Logger System

A micro data logger system[12,13] developed by Toyota Central R&D Labs., Inc. was used for piston lands pressure measurement. The data logger has a size of 34 mm × 21 mm × 7 mm and enables high-speed sampling up to 100 kHz. This system makes it possible to measure without large-scale modification of the test engine. **Figure 2** shows the micro data logger measurement system mounted on a piston assembly. It is placed inside an aluminum case and mounted on the connecting rod. A lithium primary battery as a power source is mounted on the connecting rod cap. Setting of the operation conditions and controlling the data logger is executed from the PC, and the logged data are transmitted to the PC after measurement.

In addition, this system provides light-emitting diodes (LEDs) embedded in the top and 2nd ring grooves. These LEDs are used with a transparent cylinder to distinguish the axial ring position in the groove by light leaked through the side clearance.

2. 1. 4 Oil Transport Evaluation Method

The amount of oil adhered on the combustion chamber and the intake pipe was evaluated more directly by wiping out the oil after the operation and measuring its weight. After 30 min operation under the engine braking conditions (intake pipe pressure was between −81 kPa and −86 kPa), the wide open throttle condition was performed for 180 s to purge and stabilize the amount of gathered oil.



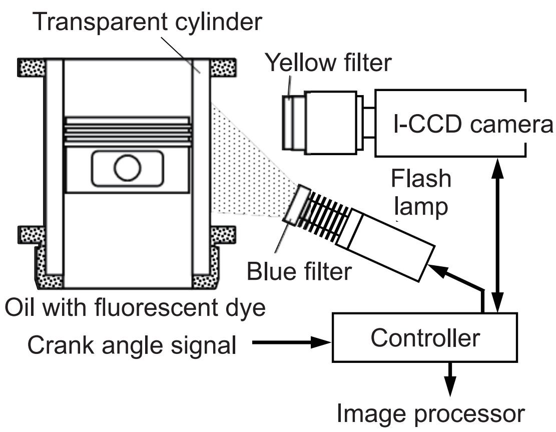


Fig. 1 Measurement system of oil film thickness distribution using 2D fluorescence method.

2. 2 Experimental Results and Discussion

Among other specifications, the end gap clearance of the top ring has a significant influence on the LOC. The piston ring specifications are shown in **Table 1**. The bar graph in **Fig. 3** shows the weight of adhered oil wiped out from the combustion chamber and the intake pipe. The weight indicates that the top ring of the smaller end gap clearance results in less LOC.

It is easy to suppose from this result that the smaller end gap clearance of the top ring interrupts the oil flow through the gap; however, this was found to be incorrect from our investigation, as follows. The photos in Fig. 3 show the states of oil distribution after 30 min operation under the engine braking conditions. The amount of oil on the 2nd land in itself was less when the top ring of the narrower end gap was used.

The amount of oil on the 2nd land was influenced by the land pressures. **Figure 4** shows the land pressures and axial ring motion during one cycle with top ring gap clearances of 0.38 mm and 0.14 mm. The 2nd land pressure with a gap clearance 0.14 mm was held higher than that for 0.38 mm. This result suggests that the narrow top ring gap suppresses gas flow through the gap, which prevents the 2nd land pressure from decreasing and maintains a sufficiently higher level than that of the combustion chamber. Therefore, the difference between the levels of the 2nd and 3rd land pressures becomes small, and oil transport from the 3rd land to the 2nd land decreases. The sudden increase in the 2nd land pressure near top dead center at the compression stroke in the narrow gap case suggests the gas flow from the combustion chamber is enhanced by the top ring axial motion, which was observed using the LED method, also shown in Fig. 4. These results suggest that higher 2nd land pressure suppresses oil

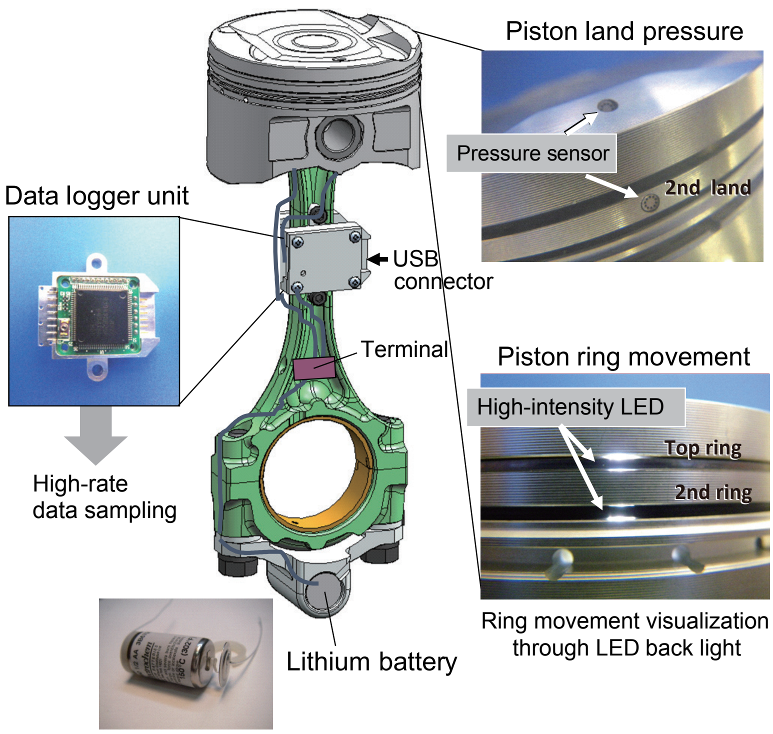


Fig. 2 Micro data logger measurement system for piston land pressure and axial ring motion.

Table 1 Specifications of piston ring pack.

	Height (mm)	Width (mm)	End gap clearance (mm)	Shape / Type
Top ring	2.5	1.2	0.38, 0.20, 0.16, 0.14	Barrel Face
2nd ring	2.8	1.2	0.5	Taper Face
Oil control ring	2.5	2.0	0.34	Barrel Face / 3-piece

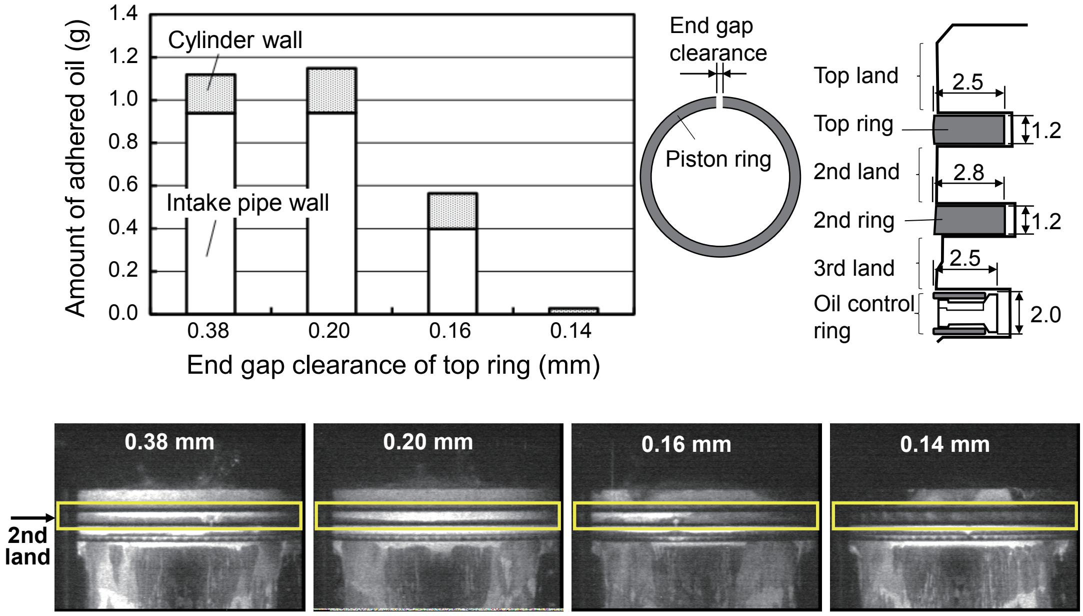


Fig. 3 Effect of top ring gap clearance on oil behavior (after 30 min operation under engine braking conditions).

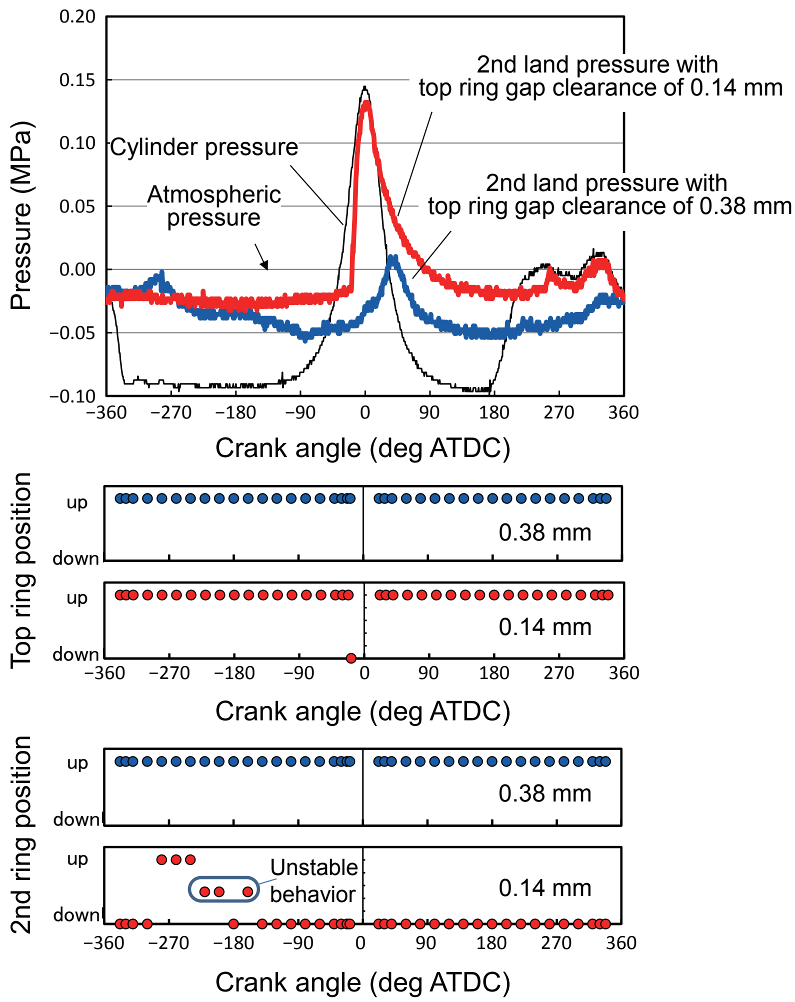


Fig. 4 Second land pressure and axial ring motion with top ring gap clearances of 0.38 mm and 0.14 mm.

transport through the ring pack.

Next, we investigated the transition of the oil distribution and the 2nd land pressure after the throttle was closed after being fully opened. **Figure 5** shows the results with a top ring gap clearance of 0.38 mm. During the 30 s after the throttle closed, the amount of oil on the 2nd land was small and the 2nd land pressure rose to more than 0.1 MPa near top dead center of the compression stroke. On the other hand, after the throttle was closed for 60 s or more, the amount of oil on the 2nd land gradually increased, and the 2nd land peak pressure became lower together with the 2nd land filled with oil. These results suggest that top ring axial motion is restricted by oil repletion. It is also possible that the lower 2nd land pressure induces more oil transport from the 3rd land to the 2nd land.

3. Oil Consumption under Middle Engine Speed Conditions

In some cases of engine development, unstable fluctuation of the LOC occurs even under steady operation. It is considered that changes of ring behavior and piston land pressure cause an increase of the LOC. In particular, reverse blow-by, which occurs when the 2nd land pressure is higher than the cylinder pressure, may influence the oil transport. Despite several hypotheses,[14] the causes of the LOC fluctuation are still not sufficiently clear. Therefore, an investigation to clarify the causes of fluctuation was performed, together with analysis of the oil distribution state on the piston at that time.

3. 1 Measurement Methods

3. 1. 1 Test Engine

A 2.2 L direct injection turbo diesel engine (bore diameter 86 mm, stroke 96 mm) was used as the test engine. The 2nd ring gap was narrower than that of the optimized engine to induce a higher 2nd land pressure than the combustion chamber pressure. The piston ring specifications are shown in **Table 2**.

3. 1. 2 Fiber Laser Induced Fluorescence Method

A fiber laser induced fluorescence (LIF) method[15,16] was adopted for oil film measurement. An optical fiber equipped in the cylinder liner scans through the axial direction on the piston and detects the oil film distribution. This system requires less engine modification and enables measurement with

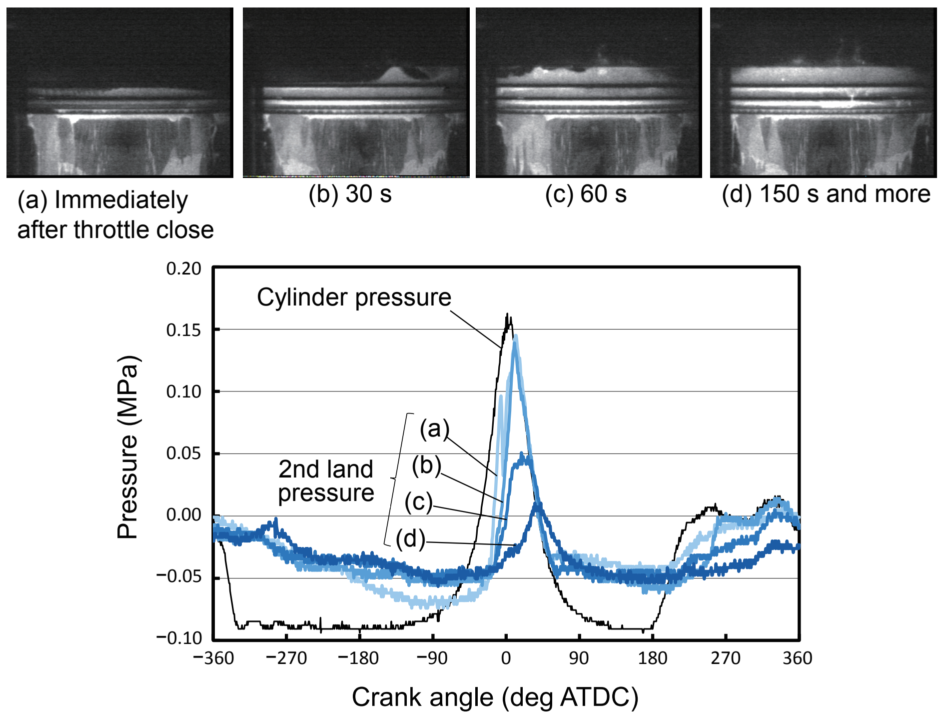


Fig. 5 Transition of 2nd land pressure and oil behavior with the throttle closed after being fully opened (top ring gap clearance of 0.38 mm).

an operating engine. **Figure 6** shows the fiber-LIF system. An optical fiber with a diameter of 50 μm is equipped in a cylinder block through a water jacket. The end of the fiber is smoothly set on the bore surface at a position 56 mm below the upper end of the cylinder. He-Cd laser light (442 nm) is irradiated onto the oil film through the fiber, which induces fluorescence. The fluorescence is detected by the same fiber, separated from the laser light by a dichroic mirror, and sent to a photomultiplier tube (PMT), which measures the intensity and translates this to film thickness.

3. 1. 3 Simultaneous Measurement of Piston Land Pressure and LOC

Changes of the 2nd land pressure and the LOC fluctuation of the No. 1 cylinder were measured simultaneously, and a relationship was demonstrated. The purpose of the 2nd land pressure measurement was only to reveal the magnitude relation to the combustion chamber pressure during the expansion stroke. Therefore, a simple method was employed.[17] A pressure sensor was attached onto a suitable position of the cylinder wall to detect the 2nd land pressure while the piston was passing by (**Fig. 7**).

A sulfur tracer method[18-21] was used to measure instantaneous oil consumption. Exhaust gas was directed to an S concentration analyzer (Horiba MEXA-1170SX). The exhaust gas was extracted at 5 mm away from the inside wall of the exhaust port to identify the LOC of each cylinder. Lubricating oil including 2% sulfur (JX HSEO) was used. To maintain accuracy, undecane with no sulfur was used as a fuel.

Table 2 Specifications of piston ring pack.

	Height (mm)	Width (mm)	End gap clearance (mm)	Shape / Type
Top ring	2.9	2.0	0.27	Barrel face
2nd ring	2.9	1.5	0.28	Taper face
Oil control ring	2.75	2.0	0.25	Barrel face / 2-piece

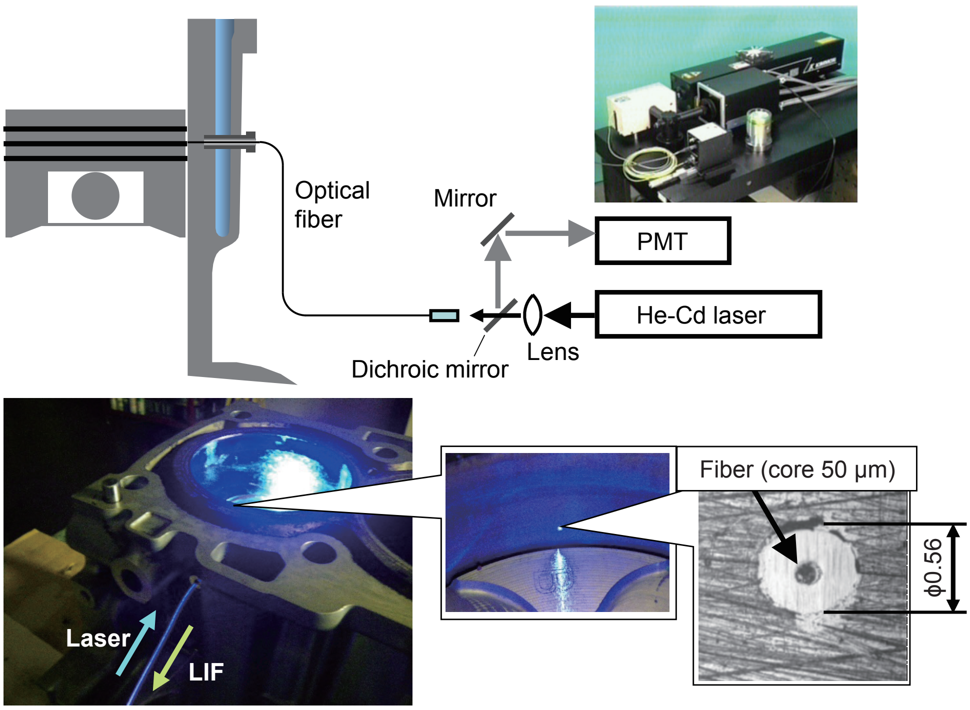


Fig. 6 Measurement system of oil film thickness using fiber-LIF method.

3. 2 Experimental Results and Discussion

Figure 7 shows the transition of the 2nd land pressure at a 130 deg ATDC in the expansion stroke and the sulfur concentration at 3600 rpm and 3150 rpm under no-load conditions. It is clear that the LOC fluctuation is synchronized with the 2nd land pressure fluctuation. The LOC increases while the 2nd land pressure exceeds the cylinder pressure during the expansion stroke. In addition, during the periods when the 2nd land pressure exceeded the cylinder pressure, the change of the 2nd land pressure indicated cyclical behavior. The lower 2nd land pressure appears in the wave bottom, especially under the condition of 3150 rpm.

The magnitude of the 2nd land pressure is related to the ring axial motion.[22-25] Specifically, the 2nd ring lift at the latter half of the compression stroke causes a gas leak from the 2nd land to the 3rd land and causes the 2nd land pressure to lower during the expansion stroke. The 2nd ring lift occurs more easily under the lower 2nd land pressure during the compression stroke because the force to press the 2nd ring down is smaller. This is the reason why the lower 2nd land pressure caused by the 2nd ling lift appeared in the wave bottom of the cyclic land pressure change. The fluctuation of the LOC tends to occur in the middle engine speed range because the total force (gas pressure, inertial force, frictional force and oil adhesion force) acting on the 2nd ring becomes close to zero under that condition.

Among the possible factors that cause the cyclic change of the 2nd land pressure, the rotation of rings in the circumferential direction was focused on. The pressure measurement from the bore side and the oil film thickness measurement using the fiber-LIF technique were conducted. The oil film distribution around the ring gap is characteristically different from that at the other circumferential portion. Therefore, the passing of the ring gap can be identified at a fixed observation point of the LIF detector.

The relation between the gap positions and the change of the 2nd land pressure was investigated. **Figure 8** shows the experimental results for 5000 cycle measurements under the 3500 rpm no-load condition. Figure 8(a) shows the pressure difference between the 2nd land and the combustion chamber at 130 deg ATDC during the expansion stroke. Figure 8(b) shows the fluorescence intensity at −240 deg ATDC (top land in the intake stroke) and −110.4 deg ATDC (lower side of top ring in the compression stroke). Figure 8(c)

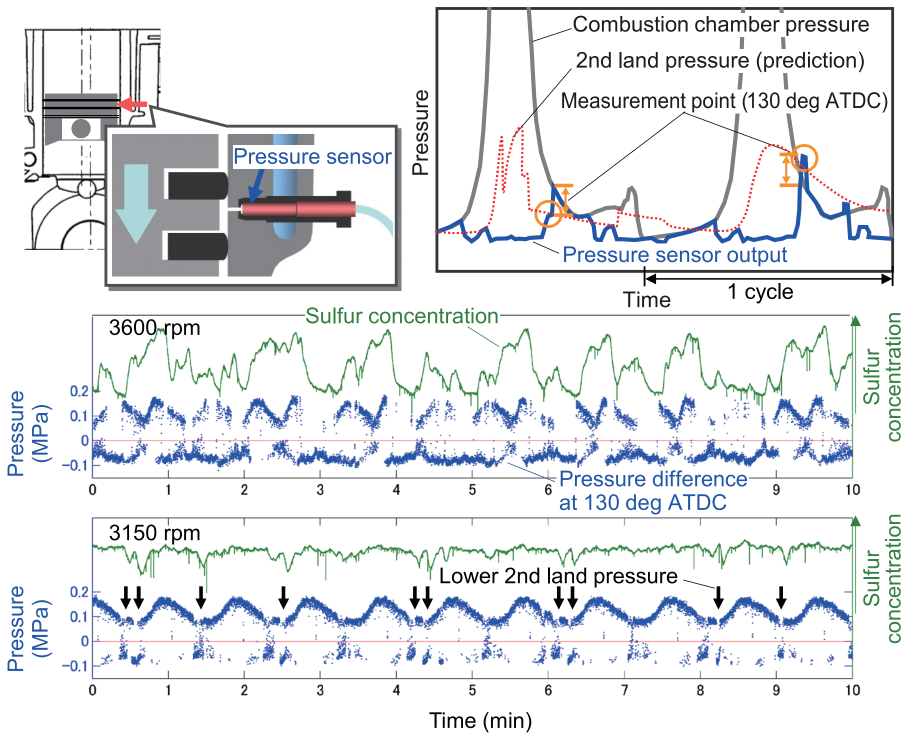


Fig. 7 Effect of pressure difference between 2nd land and combustion chamber on oil consumption.

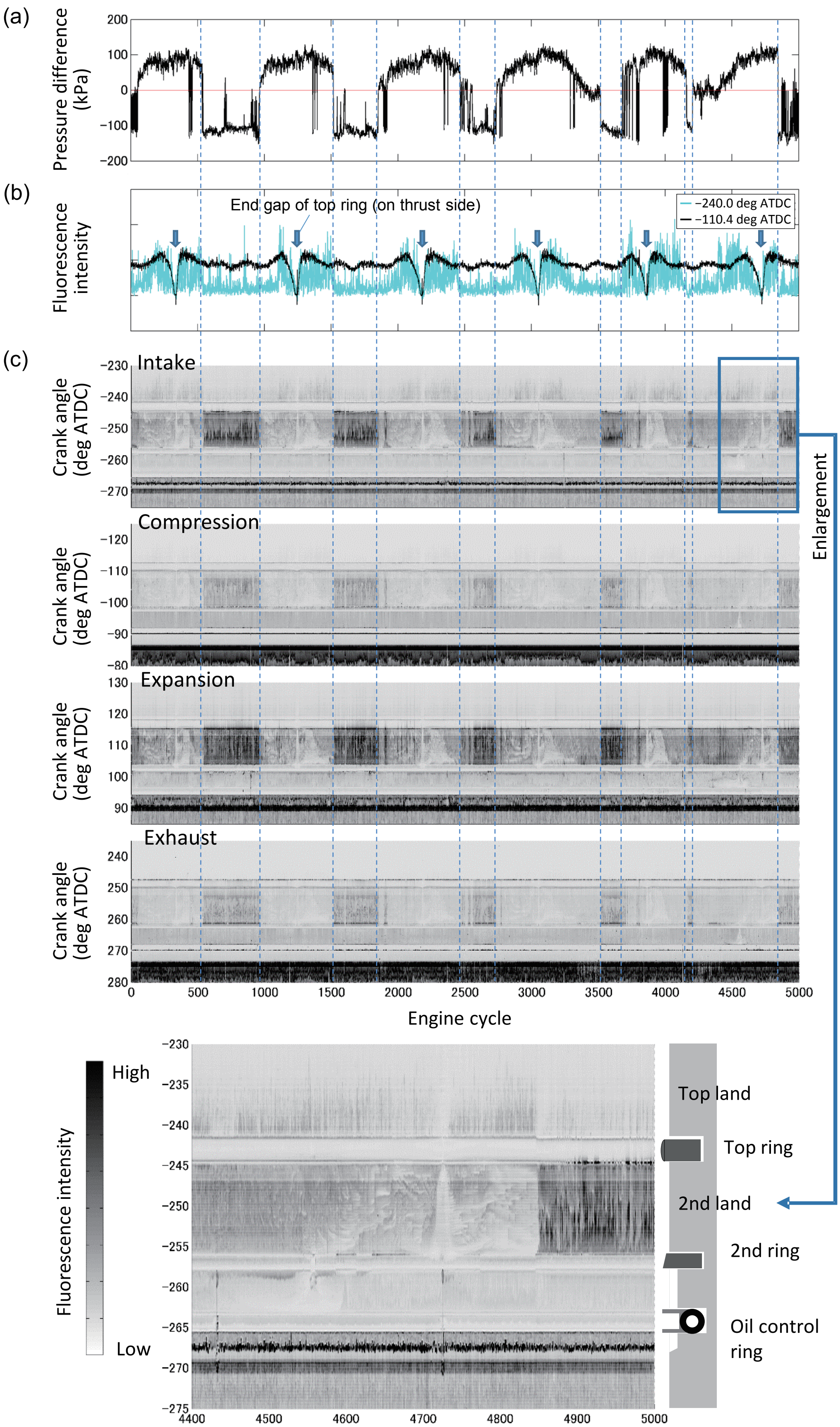


Fig. 8 Relation between 2nd land pressure and oil film on piston lands under 3500 rpm no-load condition. (a) Pressure difference between 2nd land and combustion chamber at 130 deg ATDC. (b) Fluorescence intensity (fiber-LIF) at −240 deg ATDC and −110.4 deg ATDC. (c) Distribution of fluorescence intensity.

shows the detected distribution of the fluorescence intensity around the piston land area at each stroke. The cyclic period of the 2nd land pressure fluctuation in Fig. 8(a) is almost the same as that of the top ring rotation detected by the gap signal passage in Fig. 8(b). In addition, the 2nd land pressure becomes locally highest when the top ring gap passes through the LIF sensor, i.e., comes nearest to the thrust side of the piston. If it is assumed that the rotational speed of the top ring is constant during the steady operation, then the 2nd land pressure tends to become the highest locally when the top ring gap comes to the thrust side, and lowest when the top ring gap comes to the anti-thrust side.

These tendencies can be explained by considering the change of the top ring gap area influenced by the piston secondary motion.[24] During the latter half of the compression stroke, the top ring gap area with the ring gap on the thrust side is larger than that while on the anti-thrust side because the piston moves closer to the anti-thrust side. Therefore, the gas flow from the combustion chamber to the 2nd land increases, which makes the 2nd land pressure higher while the ring gap is closer to the thrust side. According to these results, the change of the 2nd land pressure influenced by the top ring rotation proved to be one of the dominant factors that cause fluctuation of the LOC.

Next, we discuss the relation between the oil film distribution of the land area (the top land and the 2nd land) and the 2nd land pressure in the case where the 2nd land pressure is higher than that in the combustion chamber and the LOC is larger, and in the case of a lower 2nd land pressure and a smaller LOC. As shown in Figs. 8(a) and (c), the oil film at the 2nd land with higher 2nd land pressure is thinner than that with lower pressure. In addition, for a higher 2nd land pressure, the oil film at the top land becomes thicker from −241 deg ATDC to −230 deg ATDC during the intake stroke (also see Fig. 8(b) −240 deg ATDC). This result suggests that the oil transport occurs from the 2nd land toward the combustion chamber. In the former case (higher 2nd land pressure), the top ring position is shown at the bottom side of the groove from −245 deg ATDC to −241 deg ATDC during the intake stroke, while it is at the top side in the latter case (lower 2nd land pressure). The result suggests that the 2nd land pressure level affects the axial motion of the top ring.

According to this study, a decrease in the 2nd land pressure is effective to suppress the increase in the LOC. Optimization of the ring gap clearances is a valid approach to decrease the 2nd land pressure. In addition, a 2nd ring with an internal bevel or a step on the underside of the 2nd ring is effective to control the balance of the acting gas pressure.

4. Conclusions

The relation between oil transport and land pressure was investigated by adopting several novel measurement techniques, such as simultaneous use of a micro data logger and a fluorescence technique.

The following results were obtained.

• A smaller top ring gap results in smaller LOC under engine braking conditions. The main principle is that oil transport from the 3rd land to the 2nd land is suppressed by preventing a decrease of the 2nd land pressure.

• The following mechanism was clarified as the dominant factor that causes fluctuation of the LOC at the middle engine speed.

(1) Top ring rotation causes a periodical change in the 2nd land pressure level.

(2) Forces that act on the 2nd ring balance during the compression stroke under the middle engine speed condition; therefore, changing the 2nd land pressure is the dominant factor that leads to the occurrence of the 2nd ring lift.

(3) The 2nd ring motion dominates the 2nd land pressure level after the expansion stroke compared with that of the combustion chamber. This results in an increase or decrease in the amount of LOC.

These results provide some design possibilities for a reduction of the LOC, other than increasing the tensile force of the piston rings. Control of the 2nd land pressure was determined to be important under both engine braking and middle engine speed conditions.

Piston rings under lower tensile force are most effective for friction reduction, so they must not be hastily abandoned because of the trade-off effect on the LOC. The oil film phenomenon around pistons examined in this study suggest some solutions to realize both friction reduction and LOC reduction by control of the piston land pressure with design factors other than ring tensile forces.

References

(1) Kawamoto, J., Yamamoto, M. and Ito, Y., *SAE Tech. Paper* Ser., No. 740543 (1974).
(2) Kawamoto, J., Yamamoto, M., Ito, A. and Hanaoka, M., *J. Jpn. Soc. Lubri. Eng.* (in Japanese), Vol. 22, No. 11 (1977), pp. 788-795.
(3) Yamamoto, M., *Tribologist* (in Japanese), Vol. 35, No. 1 (1990), pp. 25-30.
(4) Yamamoto, M., *Tribologist* (in Japanese), Vol. 36, No. 11 (1991), pp. 905-908.
(5) Sanda, S., Saito, A., Shimura, Y., Murakami, M., Konomi, T. and Nohira, H., *JSAE Trans*. (in Japanese), Vol. 24, No. 3 (1993), pp. 128-133.
(6) Sanda, S., Inagaki, H., Fuyuto, T. and Noda, T., *Trans. JSME, C*, Vol. 64, No. 623 (1998), pp. 2653- 2658.
(7) Inagaki, H., Saito, A., Murakami, M. and Konomi, T., *SAE Tech. Paper Ser*., No. 952346 (1995).
(8) Inagaki, H., Moritani, H., Yamamoto, M. and Simura, T., *JSAE Trans*. (in Japanese), Vol. 32, No. 2 (2001), pp. 5-10.
(9) Inagaki, H., Katsumi, N., Yamada, T., Nozawa, Y. and Kawai, K., *JSAE Trans*. (in Japanese), Vol. 44, No. 2 (2013), pp. 393-398.
(10) Maeda, Y., Inoue, T., Nakada, M. and Hamada, Y., *SAE Tech. Paper Ser*., No. 860544 (1986).
(11) Ariga, S., Sui, P. C., Bailey, B., Kumakiri, T., Osumi, Y. and Sakamoto, A., *SAE Tech. Paper Ser*., No. 920652 (1992).
(12) Kimura, M., Ohsawa, M., Sunami, S., Tsuiki, H. and Imai, J., *28th SICE Sensing Forum* (in Japanese) (2011), pp. 153-158.
(13) Nozawa, Y., Kimura, M. and Inagaki, H., *JSAE Proc*. (in Japanese), No. 142-12 (2012), 20125623.
(14) Min, B.-S., Kim, J.-S., Oh, D.-Y., Choi, J.-K. and Jin, J.-H., *SAE Tech. Paper Ser*., No. 982442 (1998).
(15) Richardson, D. E. and Borman, G. L., *SAE Tech. Paper Ser*., No. 912388 (1991).
(16) Takiguchi, M., Nakayama, K., Furuhama, S. and Yoshida, H., *SAE Tech. Paper Ser*., No. 980563 (1998).
(17) Mittler, R., Mierbach, A. and Richardson, D., *Proc. Spring Tech. Conf. ASME Intern. Combust. Engine Div*. (2009), pp. 721-735.
(18) Prostak, A., *SAE Tech. Paper Ser*., No. 770065 (1977).
(19) Hanaoka, M., Ise, A., Nagasaka, N., Osawa, H., Arakawa, Y. and Obata, T., *SAE Tech. Paper Ser*., No. 790936 (1979).
(20) Hase, Y., Nakajima, Y., Nanbu, S. and Murase, I., *SAE Tech. Paper Ser*., No. 810754 (1981).
(21) Murakami, S., Nakatani, S., Nakamura, H., Miyai, M. and Kihara, N., *JSAE Proc*., No. 12-07 (2007), 20075319.
(22) Miyachika, M., Hirota, T. and Kashiyama, K., *SAE Tech. Paper Ser*., No. 840099 (1984).
(23) Yoshida, H., Yamada, M. and Kobayashi, H., *SAE Tech. Paper Ser*., No. 930995 (1993).
(24) Hitosugi, H. and Tateishi, Y., *JSAE Proc*. (in Japanese), No. 48-99 (1999), 9934032.
(25) Burnett, P. J., *SAE Tech. Paper Ser*., No. 920089 (1992).

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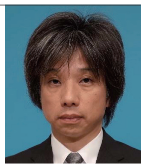

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