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Monitoring of Rotational Movements of Two Piston Rings in a Cylinder Using Radioisotopes

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Abstract

A radiotracer technique has been developed to monitor the rotational movement of two piston rings in one cylinder during engine operation. The rings were labeled with two different kinds of radioisotopes, i.e. ^{60}Co and ^{192}Ir, for identification of the top ring from the second ring. The radiotracers were implanted in a small hole bored on the inner side of each piston ring. The rings were installed in a single cylinder hydrogen engine and three NaI scintillation detectors were mounted around the engine block to measure the gamma radiation. The angle of ring-gap orientation was determined from the radiation counts measured with the three detectors during engine operation. Two windows (upper window for ^{60}Co and lower window for ^{192}Ir) were set on each ratemeter to count radiation from the two isotopes separately. Procedure to convert the radiation counts to the position of the ring gap was established. With the software programmed with MS-Visualbasic, radiation counts were compared with the reference responses that were measured at angular intervals of 10° for each piston ring in advance of the experiment. The result was used for the evaluation of the relationship between the orientation of ring-gaps and oil consumption. It was found that an increase in the oil consumption rate of a specific operation condition was closely related to the relative phase angle of the two piston rings.

Key Words : tracer, radioisotope, piston ring, ring gap, engine

1. Introduction

Radioactive tracers are used to get such information as mass flow and transfer in processes, which is hardly obtained by any other means. Over last four decades, their industrial use expanded both in routine testing and in process research and development. The automotive industry is one of the major fields of application of radiotracer technology.[1]

The rotational movement of piston rings is an important parameter in engine operation and durability. The gap location of the top compression ring has been shown to affect

Table 1. Preparation of Radiotracer

Target	Weight (mg)	Irradiation Time (min.)	Produced Nuclide	Activity (μCi)	γ-energy (MeV)
^{59}Co	4.3	50	^{60}Co	~10	1.173, 1.332
^{191}Ir	5.2	3	^{192}Ir	~50	0.296, 0.308, 0.317, 0.468

Table 2. Operation Parameters of Radiation Ratemeters

Ratemeter No.	High Voltage (Vdc)	Upper Threshold (mV)	Lower Threshold (mV)
1	752	20	1.5
2	811	20	1.5
3	752	15.1	1.5

hydrocarbon exhaust emissions[2], and engine oil consumption is closely related to the alignment of ring gaps.[3]

It appears that some rotational movement of the top compression ring is essential to prevent localized wear and deposit formation and to prevent long-term operation in a mode of high hydrocarbon emissions or high oil consumption. Therefore, a method for monitoring ring movement would be advantageous in the evaluation of new engines and in the diagnosis of certain engine field problems.[4]

Studies on the measurement of ring rotation have been performed using radioisotopes or magnetization properties. Previous radiotracer studies employed a single radioactive source and two Geiger counters positioned 90° apart to determine the rotational rate and direction[5] or a single detector and two identical sources[6]. The magnetization technique[7] employed a single magnetic proximity detector. An attempt was made using two kinds of radioisotopes and three radiation detection systems having two windows to monitor the movements of two piston rings in a cylinder simultaneously.

2. Experimental

2. 1. Preparation of Radioisotope Tracers

In order to trace two piston rings at the same time, the top ring and the second ring were labeled with ^{60}Co and ^{192}Ir, respectively and the movement of the rings were traced with three ratemeters having two windows (upper and lower). The upper window was set to count only the characteristic gamma radiation from ^{60}Co and the lower window to count both ^{192}Ir gamma-rays and the scattered ^{60}Co gamma-rays having energy in this range. To produce these radioisotopes, cobalt wire (diameter 0.7mm × length 1.5mm) and iridium sheet (width 0.6mm, length 1mm) were irradiated with neutrons in the nuclear reactor (HANARO in KAERI, thermal neutron flux: 1.7×10^{13} n cm^{-2} sec^{-1}). The irradiation time was determined so that the maximum count rate in the upper window is about 1000 cps and the counts due to ^{60}Co (top ring) and ^{192}Ir (second ring) in the lower window are the similar numbers. The weights of the targets, the irradiation-time and the produced activities are summarized in Table 1. The experiment was carried out after one week to wait the decay of short half-life radionuclides like ^{60m}Co (half-life: 10.5min), ^{194}Ir (half-life: 19.2hour). In order to implant a tracer in a piston ring, a fine hole (diameter 0.8mm × length 2.0mm) was bored on the inner side of the piston ring.

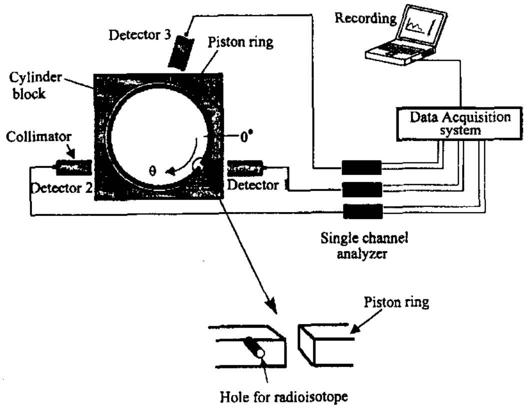

Fig. 1. Schematics of the Experimental System for the Tracing of Piston Ring Rotation

2.2. Simultaneous Tracing Technique

With the minor modification of radiation counters (Eberline E600) which have dual channel analyzers (two windows), it was possible to count γ-radiations of the different energies separately at the same time. The discrimination level to remove noise signals was set by controlling the lower threshold voltage. The window widths were set to 18.5mV for detector 1 and 2 and 13.6mV for detector 3. The operation parameters for each ratemeter were obtained to satisfy these conditions and were shown in Table 2.

In order to record radiation signals from both windows, two signal lines were extracted from the electric circuit of the ratemeter and connected to the 24-channel external counter which has been developed for tracer experiments using many detectors. As a result, characteristic radiations emitted from ^{60}Co are measured in the upper window and all the radiation from ^{192}Ir and the scattered radiation from ^{60}Co are measured in the lower window. The ratio of ^{60}Co radiation measured in the lower window to that measured in the upper window could be obtained from the calibration experiment. Thus, the radiation counts from ^{60}Co in the lower window can be estimated from the counts in the upper window and the contribution of ^{60}Co to the lower window can be removed from the total counts of the lower window to get the radiation counts from ^{192}Ir only.

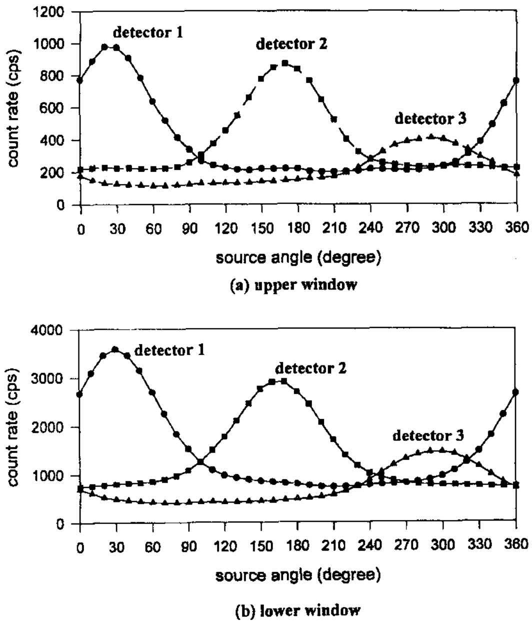

Fig. 2. Reference Responses for Top Ring Labeled with ^{60}Co

2.3. Calibration

The engine used in this study is a single-cylinder hydrogen-fuel engine, which has the same cylinder structure as the gasoline engine. The engine has the advantage in measuring the amount of burnt oil by the on-line measurement of carbon dioxide and carbon monoxide concentration in exhaust gas. The engine was coupled with an electric dynamometer installed in the engine testing room (cell), where rpm, load, temperatures of coolant and of lubricant, etc. can be monitored.

Reference responses were collected to determine

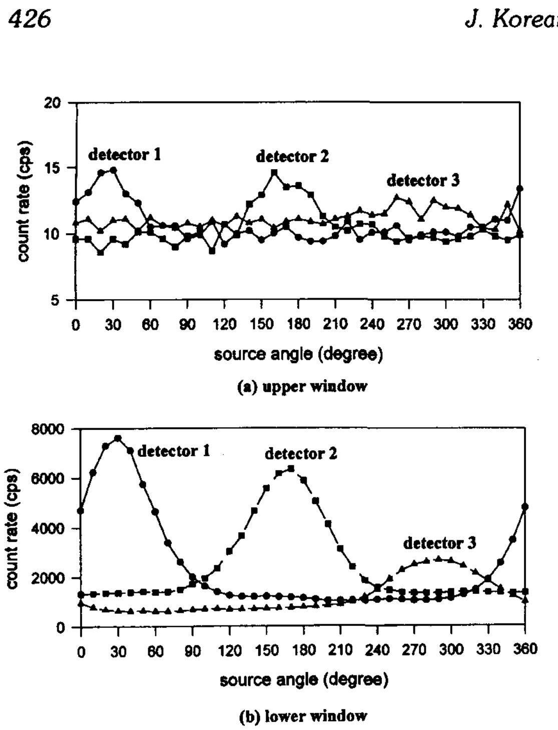

Fig. 3. *Reference Responses for 2nd Ring* Labeled with ^{192}Ir. (The rough peaks at the upper window are due to coincidence sum effect.)

the relationship between the position of ring-gap and γ-ray intensities measured in the two windows. By comparing the experimental data with the reference responses, the ring-gap position can be obtained. The engine block was surrounded by 3 NaI scintillation detectors (2″ × 2″, Eberline SPA-3) leaving an appropriate distance (1~2cm) from the engine block. To get rid of the effect of the vibration from the engine, a frame holding detectors was installed on the floor of the cell. The detectors were inserted in lead collimators to reduce background radiation. Because of the accessories and the structures installed around the engine block, the detectors could be arranged as shown in Figure 1. The gap of the top ring was fixed to the zero mark located in front of the engine and radiation was counted with the detectors during engine operation with 2000rpm by an electric

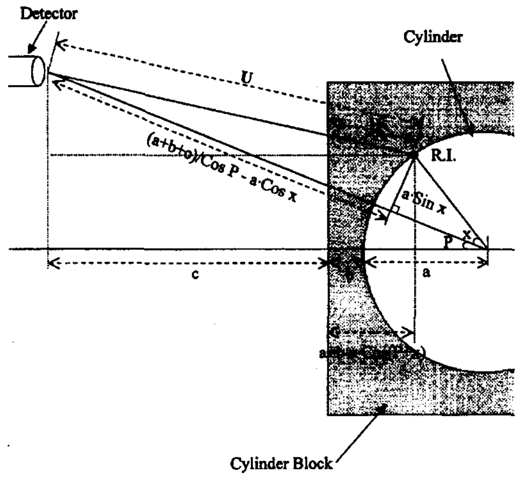

Fig. 4. Geometrical Model of Experiment for Obtaining Calibration Functions

dynamometer. The piston was then rotated by 10° to the clockwise direction to measure another count. Thirty-six determinations were made at angular intervals of 10° as shown in Figure 2. The lower count rate of detector 3 is due to the larger gap between the engine block and the detector than those of other detectors. This calibration procedure was repeated with the second ring to make reference responses as shown in Figure 3. Maximum radiation counts were measured at the 30°, 170° and 290° positions, where detector 1, 2 and 3 were deployed, respectively.

As the wall thickness of the engine block between the detector and the radiation source is not uniform, it is recommended to describe these reference responses mathematically using the model shown in Figure 4. Equation (1) was derived in the view of the geometry of detector and radioisotope.

$$f(x) = \frac{d \times e^{-mW}}{U^2} + g$$

$$U = [(\frac{a+b+c}{\cos P} - a \times \cos(x))^2 + (a \times \sin(x))^2]^{1/2}, \quad (1)$$

$$W = U \times \frac{a+b-a\times\cos(P+x)}{a+b+c-a\times\cos(P+x)}$$

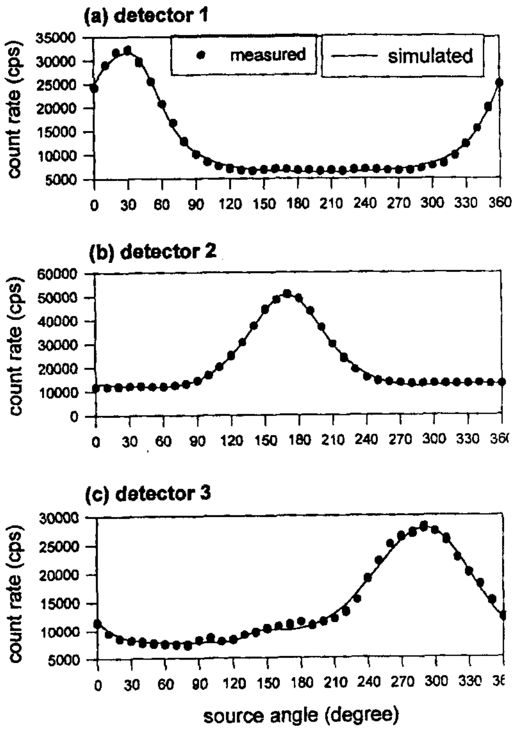

Fig. 5. Results of Curve Fitting of Reference Responses for top Ring(^{60}Co) Obtained from Upper Windows

Where f (x) is the function of radiation intensity measured when the ring gap is located at x degree with respect to the detector direction, a is the radius of ring, b is the minimum thickness of cylinder, c is the distance from the surface of engine to the center of detector, d and g are constants, m is the absorption coefficient, P is the azimuthal angle of the tracer with respect to the detector direction. Figure 5 shows the result of fitting the reference responses using equation (1) derived from the model in Figure 4. As shown in the figure the simulated curves are almost identical with the measured reference responses.

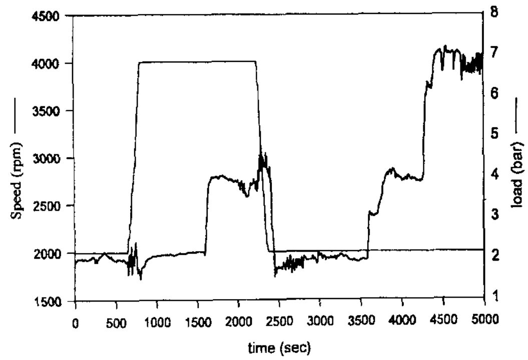

Fig. 6. Operation Condition of Engine During Experiment

2.4. Processing of Experimental Data

Both the top ring and the second ring were installed on the piston of the engine and the engine was operated with hydrogen fuel. The engine was driven at 2000 and 4000 rpm with 1/4, 1/2 and full load (wide-open throttle) as shown in Figure 6 to simulate the various driving conditions.

Figure 7 and 8 are two typical results of the experiment. The counting time of each data point was 10 seconds. To convert this experimental data to the position of ring-gap, the equations obtained from mathematical model were used in data processing. The position of a ring gap can be calculated very precisely with this procedure when sources of high activities are used to get enough radiation counts to eliminate statistical error. However, the activity used in this experiment was so small that the statistical error was not negligible. Consequently the experimental data was compared with the reference responses to find the position of the ring and a program was composed with Microsoft Visualbasic to help the comparison

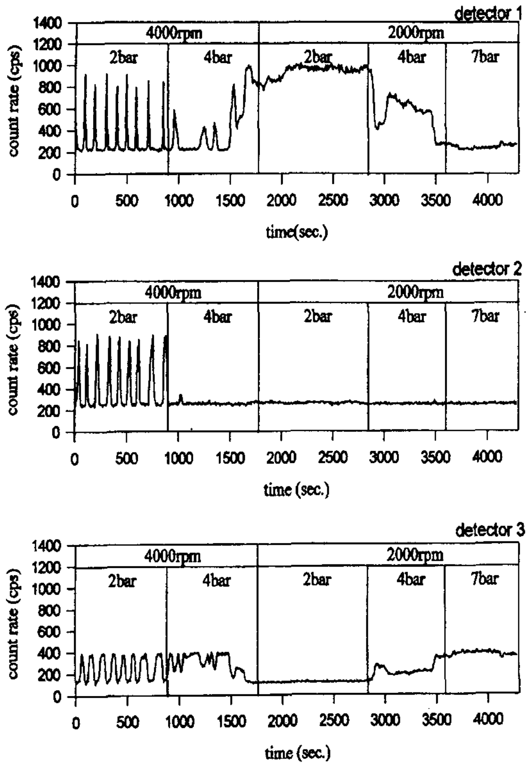

Fig. 7. Radiation Counts Measured in Upper Window with the Three Ratementers

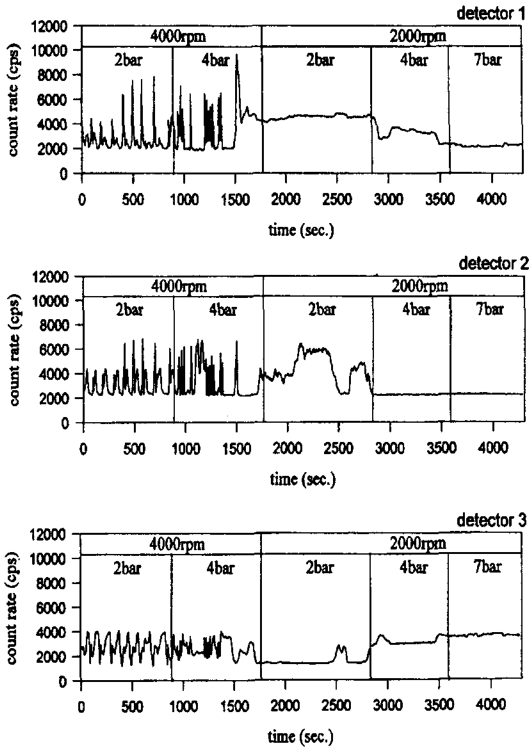

Fig. 8. Radiation Counts Measured in Lower Window with the Three Ratementers

procedure. Once the position of ^{60}Co inserted in the top ring is determined by the data recorded in the upper window, using the ratio of ^{60}Co radiation measured in the lower window to in the upper window the counts from ^{192}Ir can be obtained by extracting the contribution of ^{60}Co to the lower window. Figure 9 shows the ratio of the measured radiation emitted from ^{60}Co in the lower window to that in the upper window at every 10 degree. As shown in the figure the ratio curves have similar shapes. This phenomenon would be related to the position of detector as described in Figure 1. High values of the ratio were observed when the thickness of cylinder block between radiation source and detector increases.

3. Results and Discussion

Figure 10 shows a pattern of rotational movements of the piston rings which is obtained from the data in Figure 7 and 8. In this figure, the y-axis represents position of ring gap and the increase of ring gap angle with the lapse of time signifies that the ring rotates to clockwise direction, and vice versa.

3.1. Ring Rotation at 4000rpm (middle speed)

In 4000rpm and 2bar area in Figure 10, the top ring rotates periodically at the rate of

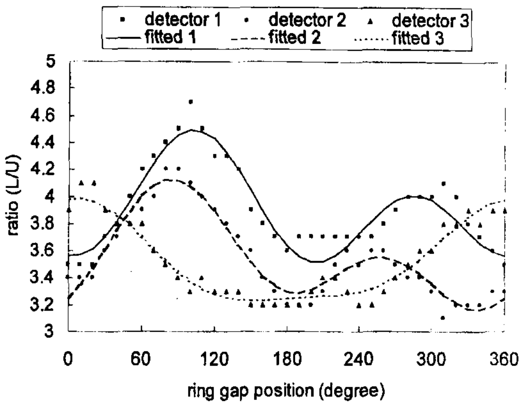

Fig. 9. Ratio of Counts Measured in Lower Window to in Upper Window for Top Ring(^{60}Co)

about 1 rev/100seconds to the clockwise direction. On the other hand the second ring is oscillating between 190° ~ 360° at the beginning of this operation condition and starts to rotate periodically to the anticlockwise direction with the similar rotation speed with the top ring' s. This means that the rotational movement of one piston ring does not affect the rotational movement of another and it is unpredictable. At the condition of 4 bar and the same speed, the top ring doesn' t show a periodic rotational motion, while the second ring rotates sometimes to the anticlockwise direction with various rates between 0.5 and 3 rev/min. But the similar rotational movement of piston ring was not observed in the several tests repeated with the same operation condition. From this result, it is understood that piston ring tends to rotates easily in middle speed and low load condition (4000rpm, 2bar) but the pattern of piston ring rotation is not always determined by an engine operation condition.

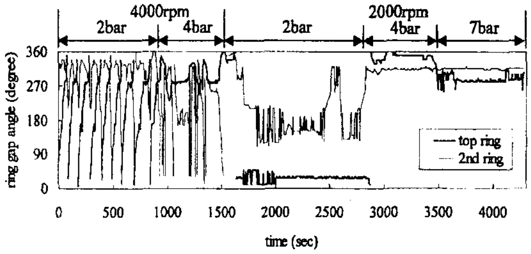

Fig. 10. Rotational Movement of Piston Rings at Various Conditions.

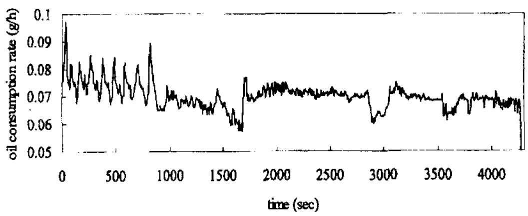

Fig. 11. Variation of Oil Consumption Rate During the Experiment

3.2.2. Ring Rotation at 2000rpm (low speed)

The top ring moves to certain position as the load changes but no more rotational movement was observed. However, as the load increases from 2bar to 4bar, the top ring moved to the rear side and settled again. The second ring, which had oscillated between 100° ~300° in 2bar condition, moved to the rear side when the load increased to 4bar and settled too. When load increased more up to 7bar, the top ring moved to a new position. From this result, it was known that the change of engine load could change the pattern of ring rotational movement: location of the ring gap or rotation speed or direction, etc.

As piston ring sometimes rotates with a high

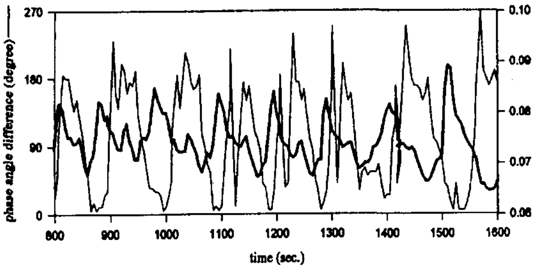

Fig. 12. Relationship of Oil Consumption Rate with Ring-gap Orientation (4000rpm, 2bar)

speed (~20 sec/rev), it is recommended to reduce the sampling time for data acquisition to observe the rapid rotational movement more clearly.

3.2.3. Relationship Between Ring Gap Position and Oil Consumption

Figure 11 shows that the oil consumption rate measured at the same time with that of Figure 10. Significant periodic increase of oil consumption is shown in 4000rpm, 2bar area. Oil consumption rate changes periodically as piston ring rotates and the periodicity of oil consumption variation agrees well with the rotational frequency of piston ring. It seems to be caused not only by rotational movement of a ring but also the relative position to another ring. To see the relationship of oil consumption with relative ring gap orientation, the phase angle difference of two piston rings and oil consumption rate were plotted in Figure 12. When the phase angle difference comes near 0°, oil consumption maximizes and as the difference increases up to 180° the oil consumption rate minimizes. From this result, it can be inferred that the possibility for oil to enter cylinder room increases when the two ring gaps are arranged at the same position.

4. Conclusions

A radiotracer technique has been developed to monitor simultaneously the rotational movements of two rings installed in one cylinder of an engine in operation. Two kinds of radioisotopes were used to label two different piston rings and two detection ranges of radiation ratemeter were set according to the characteristic γ-energies of the two radioisotopes. This method has been successfully applied to study ring rotational dynamics of the compression rings in a single-cylinder engine. The tracer technique developed here was turned out to be very useful for the study to investigate the relationship between ring-gap orientation and oil consumption.

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