Retarded Pressure Buildup behind a Rotary Engine Apex Seal*

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Experiments were made of the effects of an apex seal gap, the bottom volume of the seal slot, the overall round orifice representing all leakage passages for the combustion gas to leak out from the volume and engine speed on the retarded pressure buildup behind the apex seal using a rig attached to the head of a two-stroke cycle engine to simulate apex seal conditions in the seal slot. In addition, an analytical method for quantitative predictions of the retarded pressure buildup is presented which treats the vicinity of the seal gap as a labyrinth passage way and uses the measured discharge coefficients for both the apex seal gap and the round orifice.

Key Words : Internal Combustion Engine, Rotary Engine, Apex Seal, Retarded Pressure Buildup, Apex Seal Clearance, Discharge Coefficient

1. Introduction

The pressure behind an apex seal is one of the important factors for the apex seal to perform the proper sealing function. Under conditions of a rapid pressure rise in the combustion chamber the pressure buildup behind the seal is retarded, and a lift-off⁽¹⁾ of the apex seal from the trochoidal surface can be caused by the combustion pressure acting on its tip cylindrical surface, resulting in a spit phenomenon⁽²⁾ of the combustion gas blowing across the tip. In addition, it is urgently needed to gain a better understanding of the pressure behind the apex seal for the purpose of reducing the apex seal friction torque loss⁽³⁾. Previous papers⁽⁴⁻⁶⁾ related to the retarded pressure buildup behind the apex seal should be followed by further detailed analytical studies as done on the gas pressure between piston rings⁽⁷⁻⁹⁾.

The purpose of this paper then is to make experimental and theoretical analysis of the retarded pressure buildup. Experiments were made of the effects of the apex seal gap, the bottom volume of the seal slot, the overall round orifice representing all leakage passages for the combustion gas to leak out from the volume and engine speed on the retarded pressure buildup behind the apex seal. In an operating rotary combustion engine, making accurate and reliable measurement of the gas pressure behind the apex seal is very difficult. Therefore each factor affecting the retarded pressure buildup was simplified and the geometry of the vicinity of an apex seal was modeled under basic conditions without considering its dynamic behaviour. The correlation between the

experimental rig and an actual rotary engine is shown in Fig.1. In the theoretical analysis of the pressure behind the apex seal the vicinity of the seal is treated as a labyrinth passage way. So discharge coefficients for the seal gaps and the round orifices were measured under steady state by flowing dry air through them. In addition, by comparing the diagrams of the measured pressures behind the apex seal with the theoretically calculated pressure diagrams obtained by using different discharge coefficients for inlet seal gaps, the approximate values of the discharge coefficients for the seal gaps have been obtained, whereby the prediction of the retarded pressure buildup behind the apex seal has been made more quantitative.

Nomenclature

f : designation of the narrowest passage	
F : cross sectional area of the narrowest passage m^2	
G : mass flow rate Kg/s	
K : specific heat ratio	
N : engine speed rpm	
P : pressure Pa	
R : gas constant $J/Kg \cdot K$	
Δt : very short time s	
T : absolute temperature K	
V : volume m^3	
X : divided crank angle deg	
ϕ : discharge coefficient	
	subscripts
	1 : first volume
	2 : second volume
	3 : third volume
	m : mth volume
	12 : between 1 and 2
	23 : between 2 and 3

2. Experimental Rig and Procedure

2.1 Discharge coefficients

The posture of an apex seal does not always hold a given constant parallel seal clearance in its slot. Three possible apex seal postures, then, should be considered: (1) having a parallel gap in its slot; (2) tilting in the slot; and (3) being pressed parallel to the wall of the slot without an apparent gap. So the discharge coefficients must be obtained for the gaps of the above described postures and for the overall round orifice representing all the leakage passages. The gas mass flow through the narrowest passage from the first to the second space in Fig.

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2 can be expressed by Eq.(1). Therefore, the orifice discharge coefficient can be obtained by measuring G_{12} , F_{12} , P_1 , T_1 and P_2 .

$$G_{12} = \phi F_{12} \kappa_{12} P_1 / \sqrt{RT_1} \quad \dots\dots\dots (1)$$

$$\kappa_{12} = \sqrt{\frac{2K}{K-1} \left[\left(\frac{P_2}{P_1} \right)^{2/K} - \left(\frac{P_2}{P_1} \right)^{(K+1)/K} \right]}$$

2.2 Experimental rig and procedure for discharge coefficient

The measurement system is schematically shown in Fig.3. A pressure vessel with a built-in nichrome wire heater was placed in an electric furnace, and the air was kept at desired temperatures by controlling the variable transformers for both heaters. Temperatures of the air before the orifice and the model specimen were measured by thermocouples. The hot air having passed through the gaps or the orifices was cooled to room temperature by a heat exchanger and the mass flow of the air was measured by means of a water displacement type flow measuring tank.

Gap f_{12} , shown in Fig.4-a, corresponding to an apex seal inlet gap was a ground parallel or tapered gap having the assumed dimensions of an actual engine. The parallel gaps of eight different dimensions from 0.01 mm to 0.15 mm and tapered gaps of four different tapers were used. The tapered gaps of which inlet were wider than the outlet had the dimensions of 0.044 mm (inlet) to 0.006 mm (outlet) and 0.092 mm to 0.050 mm, and in the opposite case they had the dimensions of 0.01 mm to 0.042 mm and 0.044 mm to 0.078 mm. Each of these apex seal model specimens was bolted to the side of the pressure heating vessel head which would be used later as the head of a two-stroke cycle engine. In addition, the upper part of the specimen was also fastened with bolts to the plate having a leakage gas conduit pipe. The apex seal model specimen without an apparent gap is shown in Fig.4-b. This was attached to the side of the head and the air was introduced in the direction of a left arrow. The sealing area and line of the specimen were made equal to those of the side of an

actual apex seal, and the specimen was prepressed with a weak spring to the sealing area having a 33 mm by 2 mm rectangular hole.

Fig.4-c shows the overall round orifice representing all leakage passage ways. Six different orifices having diameters of 0.2 mm to 1.2 mm with the same length of 2 mm were used. The measurements were made at flowing air temperatures of 20 - 300 °C under pressures of 0.2 - 4 MPa.

2.3 Method of calculation for discharge coefficient

In the experimental measurement for the discharge coefficient, P_2/P_1 in Eq.(1) is smaller than the critical pressure ratio of 0.58 for air, therefore, κ_{12} can be given as a constant value of 0.685 and the discharge coefficient can be obtained by measuring the remaining parameters of P_1 and T_1 . Rearranging Eq.(1) as $G/\sqrt{T_1} = \phi F_{12} \kappa_{12} P_1 / \sqrt{R}$, and plotting $G/\sqrt{T_1}$ and P_1 on the axes of ordinates and abscissas respectively, the slope of the theoretical mass flow can be expressed as A by putting $A = F_{12} \kappa_{12} / \sqrt{R}$, since in this case, $\phi = 1$. By obtaining the slope A' from the measured values using the least squares method, the discharge coefficient $\phi = A'/A$ was determined.

2.4 Experimental rig and procedure for retarded pressure buildup

The duration in which an arbitrary leading or trailing apex seal of a rotary engine is subjected to the compression and expansion pressures can be considered to correspond to the duration of a two-stroke cycle engine running at the same speed. Furthermore, supposing the relation between the pressure in the working chamber and the output shaft angle is similar for both

Fig.1 Correlation between experimental rig and rotary engine

P_1	T_1	P_2	T_2	P_3	T_3
		F_{12}		F_{23}	
			V_2		

Fig.2 Labyrinth passage way

Fig.3 Arrangement of air flow-measuring apparatus

Fig.4 Apex seal model specimens

engines, the gas pressure of the rotary engine can be provided by operating a two-stroke cycle engine at corresponding speeds.

A simulating experimental rig of which the principal part is shown on the right in Fig.1 was employed. The pressure changes in both combustion chamber and the volume behind the seal and temperatures of the inflow gas and model specimens were measured by means of strain gage type indicators and thermocouples respectively. The measurements were made under the conditions of various inlet gaps mentioned before with the underseal volumes of 400 mm³ to 1000 mm³ and with overall round orifices of ϕ 0.2 mm at engine speeds of 500 rpm to 4000 rpm.

Although in an actual rotary engine carbon deposit around the apex seal gap is always sufficiently removed by self-cleaning effect due to apex seal motion, in the experimental rig the apex seal gap was accompanied by carbon deposit due to the stationary apex seal model specimen. Taking into consideration this deposit and the theoretical underseal pressure calculation treating air as basic gas, the experiments were performed in motoring operation in addition to firing operation.

In the case of firing operation after 2 or 3 minutes of every operation the apex seal model specimen forming the apex seal gap was disassembled to measure the thickness of carbon deposit. The indicator diagrams in the case of within 5 μ m gap decrease were adopted as data. The experimental base engine was a forced air-cooled 2-stroke cycle, 2-cylinder engine, having a displacement of 359 cc, ME24G made by Mitsubishi Motor Co.

In the case of motoring operation only one cylinder equipped with the experimental rig was compressed with the throttle wide open and with the lubricating oil feeding plunger lever in idling position. In firing operation the fuel to oil ratio was kept nearly at 100 : 1. The compression ratio of the experimental cylinder was 11, and the manual spark-advance sys-

tem was used. After checking the unnecessary gas leakage from the volume behind the apex seal model at every running condition by coating oil, the measurements were made completely without leakage.

3. Experimental Result

3.1 Discharge coefficient and $G/\sqrt{T}$

The measured results of the discharge coefficients for the parallel gaps are shown in Fig.5. The discharge coefficients become smaller as the air temperature rises and they are considerably affected by the temperature rise with a decreasing gap. Fig.6 shows the discharge coefficients for the round orifices. They are hardly affected by the air temperature and 0.9 is the average value of the discharge coefficients for the round orifices.

Figure 7 shows $G/\sqrt{T}$, corresponding to mass flow, versus pressure for the tapered gaps. The arrows in the table indicate the flow direction through the tapered gaps. The dotted line in the graph shows the parallel gaps. $G/\sqrt{T}$ for the parallel gap is almost equal to that for the tapered gap of which the narrowest dimension corresponds to the parallel gap. Therefore, the discharge coefficient for the tilting apex seal in its slot can be considered equal to that for the parallel gap corresponding to the narrowest dimension of the tapered gap.

The relation between $G/\sqrt{T}$ for the apex seal without an apparent gap and the pressure is shown in Fig.8. Similarly, in this case, the mass flow rate increases almost in proportion to the pressure. For example, comparing the curve at a temperature of 300 °C in this graph with the parallel gap of 0.01 mm indicated by the dotted line in Fig.7 at the same pressure of 4 MPa, the mass flow for the leakage of

Fig.5 Discharge coefficient for parallel gap

Fig.6 Discharge coefficient for round orifice

Fig.7 Mass flow ($G/\sqrt{T}$) for tapered gap

Fig.8 Mass flow ($G/\sqrt{T}$) for sealing area of apex seal without apparent gap

the sealing area without an apparent gap was approximately one-six hundredth of that for the parallel gap of 0.01 mm and the leakage was 6.5 cc/s at a temperature of 20 °C under atmospheric pressure. Thus, the amount of leakage through the sealing area without apparent gap was found to be extremely small.

3.2 Retarded pressure buildup

In Fig.9 the typical measured results are shown of the pressure in the combustion chamber and the pressure behind the apex seal model in the case of motoring with a gap of 0.04 mm at 4000 rpm. The pressure buildup is retarded with an increase of the volume behind the seal model, V_2 , and with an increase of the cross sectional area of the overall round orifice f_{23} , representing all leakage passages. The pressure buildup was found to be retarded considerably even in the case of no leakage as shown by $f_{23}=\phi 0.0$. The typical measured results of the retarded pressure buildup in firing operation are shown in Fig.10. In the same manner as in motoring operation the pressure buildup is retarded with an increase in engine speed, in underseal volume and in the amount of the leakage from the volume.

Figure 11-a shows a sudden pressure rise in the underseal volume which is a peculiar phenomenon occurring under heavy load during firing in the case of a large inlet gap and no or very small leakage. This pressure rise is considered to be due to the combustion of an unburned mixture and to have no influence on the pressure in the combustion chamber, which is extremely larger than the underseal volume. In the actual rotary engine, however, this phenomenon is likely to occur depending upon the conditions around apex seals, and the phenomenon can be expected to be utilized effectively for the sealing function at high engine speeds and heavy load or contrary to this case the vibration, breakage or excessive friction loss of the apex seal may be encountered.

Figure 11-b shows a typical example of a very slow pressure rise when the combustion pressure is raised rapidly at low engine speed. Fig.11-c is intended to depict the difference between the discharge coefficients for 0.04 mm gap and the round

Fig.9 Retarded pressure buildup in motoring operation

Fig.10 Retarded pressure buildup in firing operation

Fig.11 Peculiar phenomena in firing operation

orifice inlet corresponding to the cross sectional area of the gap.

The ratio of the underseal pressure to the combustion chamber pressure at the maximum difference in both pressures is shown in percentage in Figs.12 and 13 as a scale of the retarded pressure buildup by reading the pressure from the indicator diagrams for motoring and firing operations. The effect of engine speed on the pressure ratio is shown in Fig.12. $f_{12}=0$ in the table in Fig.13 represents the case when there was no leakage from the underseal volume on account of the leakage round orifice being blocked. The inlet gap, underseal volume, leakage area and engine speed were found to affect the pressure ratio. The pressure ratio for the small inlet gap was found to be very small even in the case of no leakage. As seen from Fig.13, the difference of the pressure ratio between motoring and firing operations becomes smaller for the inlet gaps of about 0.06 mm or above, since the effect of temperature on the discharge coefficient decreases with an increasing gap.

4. Analytical Calculation for Retarded Pressure Buildup

An analytical model for the pressure behind an apex seal can be obtained by ap-

plying the fundamental equation for gas pressure variation between piston rings derived by M. Eweis⁽⁹⁾ and C. Englisch⁽¹⁰⁾. The model consisting of the inlet gap and the bottom volume of the apex seal and the overall round orifice representing all leakage passages is treated as a labyrinth passage way. For the apex seal the temperature difference between the gas and the surrounding wall is very small in the same manner as for the piston ring and the term for heat transfer in the general pressure equation can be neglected. Therefore, the pressure rise dP_m is given by

$$dP_m = (RT_m/V_m) \{G_{(m-1)m} - G_{m(m+1)}\} dt \quad (2)$$

where the mass flow rate $G_{(m-1)m}$

$$G_{(m-1)m} = \varphi_{f(m-1)m} \sqrt{\frac{2k}{k-1} \frac{P_{m-1}}{V_{m-1}} \left\{ \left(\frac{P_m}{P_{m-1}} \right)^{2/k} - \left(\frac{P_m}{P_{m-1}} \right)^{(k+1)/k} \right\}} \quad (3)$$

Applying Eq.(3) to Fig.2, the pressure rise dP_i becomes

$$dP_i = \frac{RT_2}{V_2} \frac{X}{6N} \left\{ \frac{\varphi_{12} F_{12} P_1}{\sqrt{RT_1}} \kappa_{12} - \frac{\varphi_{23} f_{23} P_2}{\sqrt{RT_2}} \kappa_{23} \right\} \quad (4)$$

Fig.12 Effect of engine speed on pressure ratio

Fig.14 Effect of engine speed on retarded pressure buildup

Fig.13 Effect of dimension of parallel gap on pressure ratio

Fig.15 Effect of product of inlet gap and discharge coefficient on retarded pressure buildup

where

$$\kappa_{12} = \sqrt{\frac{2K}{K-1} \left(\left(\frac{P_2}{P_1} \right)^{k/2} - \left(\frac{P_2}{P_1} \right)^{(k+1)/k} \right)}$$

$$\kappa_{23} = \sqrt{\frac{2K}{K-1} \left(\left(\frac{P_3}{P_2} \right)^{k/2} - \left(\frac{P_3}{P_2} \right)^{(k+1)/k} \right)}$$

Equation (4) can be calculated using the measured pressures of the combustion chamber with the initial value for P_1 read from the indicator diagram at crank angle of 0 deg. and with P_1 and P_2 taken as atmospheric pressure. Successively P_1 may be obtained by adding the pressure rise dP_1 after $X/6N$ second to the former P_1 . In the range where P_1/P_2 are smaller than the critical pressure ratio of 0.528, κ_{12} and κ_{23} become 0.685 respectively. In the case when P_1 becomes lower than P_2 during the expansion process the gas changes its flow in the direction from V_2 to V_1 and V_3 . Therefore, Eq. (4) becomes

$$dP_1 = \frac{RT_2}{V_2} \frac{X}{6N} \left\{ -\frac{\varphi_{12} F_{12} P_2}{\sqrt{RT_2}} \kappa_{12} - \frac{\varphi_{23} F_{23} P_2}{\sqrt{RT_2}} \kappa_{23} \right\}$$

where

$$\kappa_{12} = \sqrt{\frac{2K}{K-1} \left(\left(\frac{P_1}{P_2} \right)^{2/K} - \left(\frac{P_1}{P_2} \right)^{(k+1)/K} \right)}$$

For the calculation of P_1 , divided crank angle X to read the measured pres-

Fig. 16 Effect of underseal temperature on retarded pressure buildup

Fig. 17 Effect of underseal volume on retarded pressure buildup

ures from the indicator diagrams was chosen as 2.5 deg., which was further divided into 10 sections to obtain P_1 by proportional allotment. Figures 14-18 show the calculated P_1 curves, which were obtained by considering each factor affecting the retarded pressure buildup behind the apex seal concerning the dimensions and the operating conditions of the actual rotary engines as well as the present experimental conditions and results. Fig. 14 shows that the pressure ratio becomes smaller at higher engine speed and it is under 30 % at 7000 rpm. Figure 15 shows the effect of the product of the dimension of the inlet gap and its discharge coefficient on P_1 , expressing the unit of the gap in mm. Assuming $\varphi_{12}=0.4$, the curves for $f_{12} \times \varphi_{12}=0.06$ corresponds to a gap of 0.15 mm and the lowest curve for 0.01 corresponds to a gap of 0.025 mm. From this figure, it is

Fig. 18 Effect of overall leakage round orifice on retarded pressure buildup

Fig. 19 Approximation of discharge coefficient in firing operation

Fig. 20 Discharge coefficients obtained by approximation

seen that P_2 is affected considerably by both the inlet gap and its discharge coefficient. As is evident from Fig.16, by raising the underseal temperature of T_2 in steps of 100 K and bringing it close to T_1 , although the measured temperature of T_2 is 475 K, the pressure buildup can be made less retarded. Fig.17 shows that the pressure buildup is retarded with an increase of the underseal volume. In the range of the round orifices shown in Fig.18, the effect of the overall leakage passage area on the retarded pressure buildup appears relatively little. Since the orifice of ϕ 1.2 mm corresponds to a gap of 0.03 mm with 70 mm width, taking ϕ for the round orifice as 0.9 and ϕ for the gap as one-half of it, taking a leakage hole as large as ϕ 1.2 mm will bring about a considerable power loss. For an actual rotary engine the leakage hole is presumed to be within the range.

Figure 19 shows a typical example of approximation of ϕ_{12} by comparing graphically the measured underseal pressure diagram with the calculated pressure diagrams assuming different discharge coefficients for the inlet gap of 0.06 mm and using the average measured value of 0.9 for the discharge coefficient for the round orifice. The shape of the calculated pressure diagram for $\phi_{12}=0.35$ agrees almost wholly with the measured one except in the neighbourhood of the maximum of P_2 .

The average values of ϕ_{12} for various conditions obtained thus are shown in Fig. 20. As the gap decreases, the discharge coefficient becomes smaller in the same manner as those obtained by measuring the mass flow. The difference in the discharge coefficient between the motoring and firing operations is considered to be due to the temperature difference as is shown in Fig.5. The values of the discharge coefficient by the approximation method are slightly smaller.

5. Conclusions

(1) The effects of each factor on the retarded pressure buildup behind an apex seal have been shown by detailed measured results.

(2) With the gap, underseal volume and leakage passage from the volume of an apex seal treated as a labyrinth passage way the factors affecting the retarded

pressure buildup can be considered. A more quantitative treatment can be made by using the approximate values of the discharge coefficients obtained by comparing the diagrams of the measured pressure behind the apex seal with the theoretically calculated pressure diagrams with different discharge coefficients.

(3) The discharge coefficients for the parallel gaps of an apex seal are much smaller than the coefficients for the round orifices of 0.9 and are approximately 0.35 to 0.6. They become smaller and are considerably affected by gas temperature as the gaps decrease, while the coefficients for the round orifices almost remain constant.

(4) The discharge coefficient for a tilting apex seal in its slot is equal to that for the parallel gap corresponding to the narrowest dimension of the tapered gap.

(5) In the case when an apex seal is being pressed parallel to the wall of the seal slot without an apparent gap, the amount of leakage is approximately one-six hundredth of that for the parallel gap of 0.01 mm and it is extremely small.

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