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On the Flow of Gas Through the Piston-Rings*

(1st Report, The Discharge Coefficient and
Temperature of Leakage Gas)

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The following terms are necessary for a theoretical quantitative study of gas leakage through the piston-rings of internal combustion engine : (1) the discharge coefficient through the narrowest gas passage, (2) the temperature of gas in the space between two rings. So at first the former is measured by letting a high temperature compressed air flow out through a gap of piston-ring set in the experimental apparatus. Next, the latter is studied using the apparatus provided with a stationary piston and a reciprocating cylinder. As a result, the following conclusions are obtained : (a) the discharge coefficients are 0.8~0.9 and its mean value is about 0.86 when the states of leakage gas are near to those of an actual working engine, (b) the temperature of gas flowing out around the piston-rings almost is equal to that of gas on the surface of piston.

1. Introduction

Author studied already on the passage of gas leaking through the piston-rings, using the Diesel engine⁽¹⁾. As the result, it was known that the passage might be considered such a labyrinth passage as shown in Fig. 1, where the narrow passage f was the gap of the piston ring in which the other leaks were also included, and the spread volume was the space between the upper piston ring and lower one. Therefore the gas leakage from the piston rings corresponded to that of the gas flow through the labyrinth, changing rapidly its properties.

M. Eweis⁽²⁾, C. Englisch⁽³⁾ and G. Eichelberg⁽⁴⁾ formulated theoretical equations and calculated the distributions of gas pressure and the quantity of leaking gas in the space between the two piston rings. Those calculations were carried out under the assumptions that the discharge coefficient through the narrowest gas passage was 1.0 and the gas did not exchange the heat with the surrounding wall. However, there was some difference between the calculated values and the experimental results, because these assumptions and the area of the narrowest gas passage are seemingly improper. So, in order to make a quantitative investigation to explain the mechanism of the gas leakage through the piston

rings, in this report the following point were made clear : (1) the discharge coefficients through the narrowest gas passage, (2) the relations between the temperature of gas in the space between two rings and the temperature of surrounding walls, and then in the 2nd Report⁽⁵⁾, the author compared the gas leakage calculated from these results with the experimental results.

Fig. 1 Passage of gas flow

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2. Discharge coefficient

Until the present, there is scarcely any report on gas flow through the port having a special form like the piston ring gap, except A. Stodola⁽⁶⁾ who studied some similar case, but it is not suitable to employ his results because its form and size were so very different from the ring gap in question. Therefore the author carried out some experiments⁽¹⁾. From the experiments of gas leakage and observation of the leakage passage in statical states, it became clear that the amount of leaking gas was almost in proportion to the size of ring gap, and the main passage of gas leakage was the ring gap, and gas passage was supposed to be as shown in Fig. 1.

Namely there was an unsteady flow through a labyrinth whose pockets v were volumes between upper and lower rings, and the narrowest passages f were products of clearance c between piston and cylinder and ring gap g . And the flux per unit time from 0 step (combustion chamber) to the 1st step pocket is given by the following equation.

$$G = \varphi f_0 \chi_{01} P_0 / \sqrt{RT_0} \quad (\text{kg/sec}) \quad (1)$$

and

$$\chi_{01} = \sqrt{2g \frac{k}{k-1} \left\{ \left(\frac{P_1}{P_0} \right)^{2/k} - \left(\frac{P_1}{P_0} \right)^{k+1/k} \right\}}$$

here, G is flux (kg/sec), φ is discharge coefficient, f is area of the narrowest passage (m^2), g is acceleration of gravity (9.8 m/sec^2), k is ratio of specific heat (1.4), P is pressure of gas (kg/m^2), T is absolute temperature of gas ($^\circ\text{K}$) and R is gas constant ($29.27 \text{ kg}\cdot\text{m/kg}\cdot\text{deg}$).

Therefore the discharge coefficient can be calculated from

$$\varphi = G_{01} / f_{01} \chi_{01} \frac{P_0}{\sqrt{RT_0}} \quad (2)$$

so the measurements were done for G_{01} , f_{01} , P_0 , T_0

Fig. 2 Comparison of experimental apparatus and actual engine in ring section

and P_1 .

2.1 Experimental apparatus for leaking flow

It is difficult to know the exact size of ring gap section and the states of gas on the actual working engine, so the apparatus with gas flow port whose form has the same functions as the ring gap section was made. Fig. 2 (a) and (b) show the ring gap section in the testing apparatus and the actual engine respectively. The ring gap section was formed with the circular parts in the actual engine, while in the apparatus it was made in a rectilinear shape to simplify the production, assembling, and handling. There was a slit whose size was c on the piston surface between piston and cylinder wall, and it corresponded to the clearance between piston and cylinder when they were closed together. In this experiment the values of c were 0.17 mm and 0.3 mm. The piston ring (3) with sectional size 3 mm $\times$ 3 mm was thrust on the lower surface of piston ring groove (1) and cylinder wall (2). These materials were made of cast iron. The ring gap g was changed by moving the ring (3). These equipments were set on one side wall of the high pressure and high temperature chamber, as shown in Fig. 3, and the compressed and heated air was supplied from the port of opposite wall to it. There were two holes to insert a thermocouple and a pressure gauge on its wall. And there was a heater which heated the air in the chamber, and thermocouples were set at the position (10) and (11) to measure the temperatures of air at the entrance and exit of the ring section. In Fig. 4, the assembly

Fig. 3 Construction of gas chamber

Fig. 4 Arrangement of experiment apparatus

Fig. 5

Fig. 6

(a)

(b)

●... $p_c = 10 \text{ kg/cm}^2$, ○... $p_c = 20 \text{ kg/cm}^2$, ×... $p_c = 30 \text{ kg/cm}^2$, ⊙... $p_c = 40 \text{ kg/cm}^2$

Fig. 7 Discharge coefficients of gas through ring gap

was given, and the air which flowed from the high compressed air tank ② into the chamber ① was controlled by the valve ③. The leaking air was measured with the float tank ④ under various combinations of the area of passage, pressure and temperature of air in the chamber.

2.2 Experimental results

Fig. 5 shows some experimental results. As it is seen from this figure, some leakage through the other parts than the ring gap could not be prevented due to the technical difficulty, so this leakage was deducted from the total value to correct the amount of leaking air. Fig. 6 shows an example of such correction of results. Substituting the corrected leakage value in Eq. (2), the discharge coefficients as shown in Fig. 7 (a) and (b) were obtained. From those results, it was seen that the discharge coefficients were not affected by the pressures, temperatures of leaking gas, the piston clearance and the size of ring gap, and its mean value was about 0.86.

3. Temperature of leaking gas

It is imagined that there is considerable heat exchange between cylinder wall, piston and piston rings, when the high temperature and pressure gas flows through the ring sections, because its passage is very narrow and mazy, besides the piston does a

relative motion with the cylinder. But M. Eweis and others treated the gas flow as a process without heat exchange, and there is scarcely any report on the heat transmission of gas at the ring section. In former days W. Nesselt⁽⁷⁾, R. N. Janeway⁽⁸⁾, G. Eichelberg⁽⁹⁾ and others attempted to study the coefficients of heat transfer between combustion gas and cylinder wall, and they thought that its values were about $300 \text{ kcal/m}^2\text{hr}^\circ\text{C}$ or more. But, since the coefficients at the ring section are considered larger than those in the combustion chamber, the author studied the heat exchange in the ring section experimentally.

At first the temperatures and pressures of gas flowing through the ring section were measured, and then the heat transfer coefficients were calculated on the results of experiments. Moreover, using the heat transfer coefficients considered to be near by equal to that in the actual engine, the gas temperatures at the ring section were computed and the calculated values were compared with the measured values.

3.1 Apparatus for leaking gas temperature

The high temperature and pressure air was supplied to the narrowest passage of the ring section and its temperature and pressure had to be measured. For this apparatus, a stationary piston and a reciprocating cylinder were prepared. Figs. 8 and 9 illus-

① piston, ② cylinder, ③ supporter, ④ cylinder guide, ⑤ connecting rod, ⑥ stop ring, ⑦ normal ring, ⑧ water jacket, ⑨ combustion chamber, ⑩ entrance of compressed gas, ⑪ heater joint, ⑫ pipe of pressure gauge, ⑬ pipe of thermocouple guide, ⑭ measuring point of cylinder temperature, ⑮ thermocouple guide, ⑯ spring

Fig. 8 Measurement apparatus of gas temperature

Fig. 9

trate the assembly of main section of the apparatus and its photograph. The section of stationary piston is shown in Fig. 10. The terminal of heater (18) and the entrance of compressed air are set up on the upper and (17) of the piston (1), and the compressed air is heated in the heating chamber (20), furthermore it enters the ring section through the combustion chamber (9). (6) is the ring to prevent the leakage air from the combustion chamber to the upper room. The back pressures of the 1st ring and the 2nd ring were measured, by leading those pressures to the gauge through (24) and (25). The points (●) are positions at which the temperatures of piston surface were measured, and small circles (○) are positions at which the temperatures of gas flowing through passage were measured with the thermocouples which are described in the following. Further the amount of leaking gas through the ring section was led into the flow meter through the passage (26) and the hole (27). The installing method of thermocouple hot junction to measure the temperature of gas flowing through the passage is shown in Fig. 11 (a). The insulator was painted on the surface of pits, besides, a thin mica plate (5) was put on it, and as a result a space 1.0 mm deep was obtained. By blasting this junction with a high temperature and pressure air, it was ascertained that the junction did not touch its surrounding and the indicated temperature was equal to the temperature of air. In Fig. 11

(b), the setting of thermocouple to measure the temperature of piston surface and cylinder wall is shown. The leads of thermocouple were made of copper and constantan whose diameters were 0.15 mm both and they were covered with an insulator.

The piston used was made of cast iron and its diameter was 76 mm, and had the same size as the upper parts of piston of which Diesel engine was used as before to measure gas leakage. Cylinder stroke was 90 mm, its material and size were same as those of the cylinder which had been shown in "A Dynamic Theory of Piston Ring Lubrication (2nd Report)"⁽¹⁰⁾. To measure the temperature of cylinder inner surface, the thermocouples were fixed at three points on its surface perpendicularly by means of the above method, and those wires were led to the meter with a spring fixed on the upper part of cylinder. By this method, it was possible to continue measurements for a long time until about 2000 r.p.m. in crank revolution. Fig. 12 shows the leading equipments of wire and the cylinder. As shown by Fig. 8, there was a water jacket on the outside of the cylinder guide.

3.2 The results of experiments

(i) The gas temperature Making the cylinder reciprocate at 1000 r.p.m. of crank revolution, changing the temperature (100°C~400°C) and pressure (10~30 kg/cm²) of air in the combustion chamber, the experiments were performed. In Fig. 13

Fig. 10 Test piston

Fig. 11 Construction of hot junction

(a), (b) and (c), some examples of measurements are shown. From the results, it is seen that the values of gas temperature are very close to the piston temperature, although the former is lower than the latter especially in the ring section. This phenomenon is understandable from the fact that the temperature of cylinder inside is fairly lower than the temperature of piston. As is evident from these results, it is a false idea that the gas flows through the ring section without any heat exchange with the surrounding wall, rather it seems to be proper that the temperature of gas is nearly equal to that of piston surface.

(ii) Heat transfer coefficient In the case of calculating heat transfer coefficients between the gas and its surroundings on the ring section, from such results the accuracy for calculation may be poor, because the difference between two temperatures is very small as stated above. Then the heat transfer coefficients between the piston crown and the gas on its surroundings 1~4 [see Fig. 13 (a)], which are judged to be comparatively close to that on the ring section, were calculated. The heat transferred between the gas through passage and its surrounding is given per time dt as follows

$$Gc_p(t_1 - t_3)dt = F\alpha(t_m - t_w)dt$$

here, G is amount of leaking gas (kg/hr), c_p is specific heat of air under constant-pressure (kcal/kg°C),

Fig. 12

(c) $P = 30 \text{ kg/cm}^2$
Solid line is temperature of surface of wall
dotted and chain lines are temperature of gas
Fig. 13 Measurement results

Table 1 Examples of calculating results of α

P kg/cm ²	t_1 °C	t_2 °C	t_3 °C	t_4 °C	t_c °C	G kg/sec	α kcal/m ² hr°C	w m/sec
10	100	87	79	77	51	0.594×10^{-3}	206	7.00
20	"	94	87	84	54	1.047	225	6.50
30	"	97	89	87	66	1.334	374	5.64
10	200	112	104	102	58	0.374	178	4.85
20	"	125	120	115	71	1.031	440	7.08
30	"	125	125	115	101	1.339	668	6.25
10	300	125	117	110	77	0.445	252	6.22
20	"	139	128	124	89	1.081	618	8.00
30	"	147	142	127	106	1.300	740	6.56
10	400	148	130	128	100	0.403	255	6.06
20	"	160	146	140	106	0.991	596	7.87
30	"	172	168	150	120	1.274	733	6.94

t_1 and t_3 are temperatures of gas at entrance and exit (°C), $t_m = (t_1 + t_3)/2$ is mean temperature of gas in the positions 1 and 3 (°C), $t_w = \{t_c + (t_2 + t_4)/2\}/2$ is mean temperature of surface of surrounding (°C), t_c is mean temperature of cylinder (°C), F is area of surrounding (m²). Therefore

$$\alpha = \frac{Gc_p(t_1 - t_3)}{F(t_m - t_w)} \quad \text{kcal/m}^2\text{hr}^\circ\text{C} \quad (3)$$

Substituting the measurement values into this equation, the calculated results are shown in Table 1. According to them, the heat transfer coefficients are about 200~700 kcal/m²hr°C corresponding to the amount of leaking gas. Those values are slightly larger than the values between combustion gas and cylinder wall, which were seen in Eichelberg etc's reports, but in these experiments, those values are supposed to be proper because the cylinder is moving against the gas and its passage is very narrow. Consequently, on the ring section which is discussed in the report, as the passage is very narrow and complex and its turnings are more numerous, it is estimated to have more large values. Accordingly it was farther clarified by the following calculations.

(iii) Temperatures by calculations When we substitute the above heat transfer coefficients into the equations of exchange of properties of leakage gas which will be stated in 2nd Report, the gas temperature is calculated on 2 rings and passage area 0.11 mm². Fig. 14 shows these results. Namely the gas temperature in the case of $\alpha = 100$ kcal/m²hr°C is much smaller than that of adiabatic flow. If heat transfer coefficient is assumed 300 kcal/m²hr°C the temperature of ring land become nearly equal to the gas temperature on its surroundings, and then it seems rather proper to consider that the gas temperature is nearly equal to the piston temperature. Therefore it is obvious that the temperature of leaking gas is nearly equal to that of surface of ring section.

Fig. 14 Relation between heat transfer coefficient and gas temperature

4. Conclusion

From the above studies on the gas flow through the ring section, the following are made clear. (1) the discharge coefficients are 0.8~0.9 and its mean value is about 0.86 in the case of the gas which has similar properties of working gas to the actual engine and flows through the narrowest passage, (2) heat transfer coefficients between the gas and its surroundings are 200~700 kcal/m²hr°C even in front of the 1st ring and the temperature of gas through the ring section is near by equal to that of surface of the ring section.

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