On the Flow of Gas Through the Piston-Rings*

(2nd Report, The Character of Gas Leakage)

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The measuring values of the discharge coefficient and the temperature of a gas flowing through the piston-rings which were obtained in 1st Report, are used to calculate the amount of the leakage gas and its pressure distribution under several conditions of the piston-rings. And comparing these calculated results with the previous experimental ones, the following conclusions are reached; (1) The calculation and experimental values are consistent in results, (2) the mechanism of gas leakage through the piston-rings corresponds to that of a gas flowing through the labyrinth, changing rapidly its properties, (3) especially, the unsteadiness of leakage flow produces an interesting effect upon the gastightness, (4) and it is also proved that the leaking gas hard y contains combustion gas when estimated from the theoretical calculation.

1. Introduction

The discharge coefficient and the states of heat exchange between the gas and the wall surrounding it, which are necessary to calculate the flow of the leaking gas through the piston rings, were gained through the experiments in the 1st Report(1). In this report, the theoretical calculations on the gas leakage through the rings and comparisons of their results with the measured values which were gained some years ago were tried(2), using the above mentioned results, and as the result, we succeeded in quantitative investigation and new phenomena on the character of gas leakage were found out. In this study, the following points are different from the former: (1) The passage area of ring gap is the product of measure of gap and allowance of the radius of the cylinder and the piston ring land independently of the form of ring ends, i.e. whether the ends are rectangular, step, or inclined. (2) When the gas pressure on the back of ring is higher than that on the combustion chamber side from the ring, the ring is lifted, the area of passage is spread, and the pressures on both side are balanced at once. (3) The relations between the ring gap and the area of the narrowest passage in the actual engine and the narrowest passage that was used for calculations were made clear, and comparison between the calculated results and the measured values of gas leakage in the actual engine was tried. (4) From the results in the 1st Report(3), the gas is assumed to be flowing with a temperature nearly equal to that of piston, and the discharge coefficient of gas through the gap is 0.86. (5) The consistency of combustion gas in the leaking gas was analysed for each time and place.

2. Numerical formula

2.1 Numerical formula for gas leakage

The passage of gas through N-rings is a labyrinth consisting of N−1 rooms each with a volume \( V \), which are divided with the narrowest passage area \( f \). If there is no crevice between the ring outside and the cylinder wall, or between the ring lower surface and the groove surface, \( f \) will be the product of the piston clearance \( c \) and the ring gap \( g \). But in practice the gas leaks out through the above parts, so those passage areas are calculated in terms of the equivalent area for gap section according to the character of gas leakage of actual engine, and all leaks can be represented with the area of ring gap section. Following notations are used: \( P \) is the absolute pressure (kg/m²), \( V \) is the volume (m³), \( T \) is the absolute temperature of gas (°K), \( F \) is the area of surface of each room (m²), \( k \) is the ratio of specific heat (1.4), \( v \) is the specific volume of gas (m³/kg), \( c_s \) is the specific heat for the constant volume, \( \alpha_s \) is the heat transfer coefficient between the gas and its surrounding (kcal/m²hr°C), \( f_{(m+1)} \) is the area of the narrowest passage between \( m \) step room and \( m+1 \)

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step room (m²), \( \varphi \) is the discharge coefficient at \( f \), \( G_m \) is the gas weight in \( m \) step room (kg), \( G_{m(m+1)} \) is the gas flux from \( m \) step to \( m+1 \) step (kg/sec), \( m \) is the symbol shown \( m \) step room, \( P_0 \) is the pressure in front of 1st ring and is assumed to be equal to that in the combustion chamber. In the case of calculations for the characteristic variation of gas in the \( m \) step room after time \( dt \), the following are assumed, i.e. in each room, the gas is in steady states for very short time \( dt \), the whole velocity energy of gases entering through the narrowest passage into the following room changed to a heat energy there.

(a) Case of \( P_{m-1} > P_m > P_{m+1} \)

As shown in Fig.1 (a), \( dG_{m(m+1)} \) flows from \( m-1 \) step room to \( m \) step room, \( dG_{m(m+1)} \) flows from \( m \) step to \( m+1 \) step room, the equations on variation of pressure, temperature and flux of gases per \( dt \) in \( m \) step room are as follows:

\[
\begin{align*}
    dP_m &= (\frac{k}{R/V_m}) \left[ G_{m(m-1)} m T_{m-1} - G_{m(m+1)} m T_m - (F_m c_m c_k) (T_m - T_{wm}) \right] dt \quad \text{(1)} \\
    dT_m &= (\frac{RT_n}{P_m V_m}) \left[ G_{m(m-1)} m (k T_{m-1} - T_m) - G_{m(m+1)} m (k-1) T_m - (F_m c_m c_k) (T_m - T_{wm}) \right] dt \quad \text{(2)} \\
    dG_m &= dG_{m(m-1)} m - dG_{m(m+1)} m = [G_{m(m-1)} m - G_{m(m+1)} m] dt \quad \text{(3)}
\end{align*}
\]

and

\[
G_{m(m-1)} m = \varphi f_{m(m-1)} m \sqrt{\frac{2 pk}{h-1} \frac{P_{m-1}}{V_{m-1}}} \left\{ \left( \frac{P_m}{P_{m-1}} \right)^{\frac{k-1}{h}} - \left( \frac{P_{m-1}}{P_m} \right)^{\frac{k+1}{h}} \right\} \quad \text{(4)}
\]

As to be known from 1st Report, in this case it is supposed to be \( T_m = T_{wm} \), because of a large heat exchange between gases and its simple as follows:

\[
\begin{align*}
    dT_m &= 0 \\
    dP_m &= (\frac{RT_{wm}}{V_m}) \left[ G_{m(m-1)} m - G_{m(m+1)} m \right] dt \quad \text{(5)}
\end{align*}
\]

In the latter half of calculations, the pressure relations of \( P_5 = P_1 \) and \( P_0 = P_1 = P_5 \) appear. To subsequent calculations, M. Eweis and others go on, assuming that the narrowest passage area is constant, and the results sometimes show that the pressure of crank case side becomes higher than that of combustion chamber side. But when the force acting on the ring is considered, the friction force works toward the combustion chamber, the direction of inertia force does toward the crank case but its value is very small except in the case of high speed in the neighborhood of B.D.C., therefore the ring is lifted from the lower surface of groove, the passage area is much spread out, and the gas pressure decreases immediately, so it is considered proper to think that the pressure on the lower side of the ring can not become higher than that of the upper side. Thereupon in the above case, the following methods (b) and (c) were employed.

(b) Case after \( P_0 = P_1 \)

This is a case shown in Fig.1 (b). At first the flux \( G_{12} \) is calculated with the ratio of pressure in the 1st step room to that in 2nd step room. Next, when the pressure drop \( dP'_1 \) resulting from \( G_{12} \) is larger than \( dP_0 \) in 0 step room (combustion chamber), the flux between 0 step room and 1 step room is zero, but when \( dP_0 > dP'_1 \), \( G_{12} \) which corresponds to \( dP_0 - dP'_1 \) flows backward, and \( dP_1 \) becomes equal to \( dP_0 \), therefore

\[
G_{12} = \varphi f_{12} \sqrt{\frac{F_1}{2 R T_1}} \quad \text{(6)}
\]

from Eq. (5)

\[
\begin{align*}
    dP_1 &= -(\frac{RT_1}{V_1}) (G_{10} + G_{12}) dt \\
    \therefore \quad G_{10} &= -(V dP_1 / RT_1 dt) - G_{12} \quad \text{(7)}
\end{align*}
\]

thereupon

\[
\begin{align*}
    dP_1 &= dP_0 \\
    \text{(c) Case after } P_0 &= P_1 = P_5
\end{align*}
\]
This is a case shown in Fig. 1 (c).
Similarly
\[ G_{32} = \varphi f_2 x_m P_3 / \sqrt{RT_2} \] .......................... (8)
\[ G_{31} = - (V_d P_2 / RT_2 dt) - G_{32} \] .......................... (9)

thereupon \( dP_2 = dP_0 \). Considering that \( G_{21} \) enters from
2nd step to 1st step and \( G_{10} \) flows out from 1st to
0 step, the next equation is obtained.
\[ G_{10} = G_{21} - (V_d P_1 / RT_2 dt) \] .......................... (10)

thereupon
\[ dP_1 = dP_0. \]

2-2 The equation for the consistency of commu-
bus gas in the leaking gas

It was reported in the experiments by Williams\(^{(4)}\)
or the author\(^{(3)}\) that the content of CO\(_2\) was very little
in the leaking gas, so the author studied analyti-
cally this phenomenon.

For the interval \( dt_m \), the gas \( G_{m+1} \) kg exists in
m step room \( V_m \), and the consistency of combustion
gas which is contained in it is \( [x_m] \). \( x \) is supposed
that the combustion chamber \( V_c \) is filled with a
combustion gas at the maximum pressure in the
indicator diagram, until this moment the air exists
alone in the ring sections. The combustion gas leaks
out from \( V_c \) to \( V_2 \) through \( V_1 \) as shown in Fig. 2,
but also its flow may be as follows because of its
possibility to backward as stated before.

(a) Case of all gas flowing in the direction of
the crank case

The quantity of gas \( G_{m+1} \) kg flows from \( m-1 \) step room to \( m \) step room with its consistency \( [x_{m-1}] \),
and \( G_{m+1} \) kg flows from \( m \) step room to \( m+1 \) step room with its consistency \( [x_m] \). Therefore,
for the interval \( dt_{m-1} \), the quantity and consistency of gas which exists in \( m \) step room are given as follows:
\[ G_{m+1} = ([G_{m+1}] - G_{m+1}) + G_{m+1} \] .......................... (11)
\[ [x_m] = ([G_{m+1}] - G_{m+1}) + ([G_{m+1}] - G_{m+1}) \]
\[ = [G_{m+1}] / [G_{m+1}] \] .......................... (12)

(b) Case of the gas flowing from \( m \) step room to \( m-1 \) and
\( m+1 \) step rooms

In this case, the consistency does not change in
\( m \) step room.

(c) Case of the gas flowing from \( m-1 \) and
\( m+1 \) step rooms to \( m \) step room
\[ G_{m+1} = [G_{m+1}] + G_{m+1} + G_{m+1} \] .......................... (13)
\[ [x_{m+1}] = ([G_{m+1}] + G_{m+1} + G_{m+1}) / [G_{m+1}] \]
\[ = G_{m+1} / [G_{m+1}] \] .......................... (14)

(d) Case of the gas flowing backward from
\( m+1 \) step room to \( m \) step room and from \( m \) step room to \( m-1 \) step room
\[ G_{m+1} = [G_{m+1}] + G_{m+1} + G_{m+1} \] .......................... (15)
\[ [x_{m+1}] = ([G_{m+1}] + G_{m+1} + G_{m+1}) / [G_{m+1}] \]
\[ = G_{m+1} / [G_{m+1}] \] .......................... (16)

When \( G_{m+1} \) is the quantity of leaking gas per \( dt \),
\( [x_{m+1}] \) is its consistency, \( G \) is the quantity of leaking
gas per one cycle, and \( [x] \) is its consistency, we get:
\[ [x] = \sum [G_{m+1}] / [G_{m+1}] \] .......................... (17)

Next, if \( CO_2 \) is the ratio of \( CO_2 \) in combustion
gas components, the ratio of \( CO_2 \) in leaking gas
is given as follows:
\[ [x_{CO_2}] = [x] \times [CO_2] \] .......................... (18)

3. Calculating method

The calculation was made on Yanmar Diesel engine\(^{(2)}\), which had been used by the author some years ago. The distribution of piston temperature was measured by means of the thermocouple which was planted on the piston surface of this engine and connected with the link, and its values were employed for calculation. Fig. 3 shows the distributions of temperature on the piston surface. There is no common solution of the equation for gas leakage, so dividing a cycle into the interval \( dt \), we calculated the properties and the quantity of leakage gas. The shorter \( dt \) was, the more correct the calculating results became. Further, the following method was employed to compare the area of the narrowest passage in the calculation with that in the actual engine. If \( f_x \) and \( f_o \) are the gas passage areas at
the ring gap and at the parts beyond that, and \( \varphi_x \) and \( \varphi_o \) are discharge coefficients at \( f_x \) and \( f_o \),
the quantity of leaked gas \( G \) is proportional to the product of total area \( f \) of gas passage and the
discharge coefficient \( \varphi \). As \( K \) is a constant, we get
\[ G = K \times \varphi \] .......................... (19)
If all leaks are represented with the area $f$ of ring gap section,

$$G = K_f \varphi_0$$  

(20)

from Eqs. (19) and (20)

$$f = f_0 + \left(f_0 \varphi_0 / \varphi_2 \right)$$  

(21)

From experimental results, $f_0 \varphi_0$ is gained as shown in Fig. 4. If $\varphi_2$ which was reported in the 1st Report is used, the relation between the area $f_0$ and $f$ is obtained.

Fig. 3 Piston temperature

Fig. 4 Method to get $f_0 \varphi_0$ from experimental values

Fig. 5 Comparison of M. Ewein's and our way of calculation
4. Comparison of the calculating and the experimental results

4.1 Comparison of M. Eweiss's\(^{(2)}\) with our way of calculation

Figs. 5 (a) and (b) show the calculating results which were obtained with the former method and ours. The upper diagrams give transitions of pressures \(P_1\) and \(P_2\) in 2 rooms and the lower one indicates the progress of leaking gas which flows from 2nd step room to the crank case. In Fig. 5 (a), it was \(P_1 > P_0\) and the quantity of leaking gas was 5.6 l/min, and in Fig. 5 (b) 5.2 l/min was obtained. On the other hand the experimental result was 5.07 l/min\(^{(2)}\), so the case of (b) is close to an actual case.

4.2 Various conditions and gas leakage

(a) The area of passage and gas leakage

Fig. 6 shows comparison between calculated results and measuring value on a variety of the passage areas. It is known that the ring gap is an important component influencing upon gas leakage.

(b) Number of rings and gas leakage

In Fig. 7, a comparison of quantity of leaking gas in the case of using the number of rings 1~4 with \(f = 0.142 \times 10^{-6}\) m\(^2\) is shown. When 4 rings were used, the experimental value of leaking gas was comparatively large: may be it is due to the poor contact of the lower surface of ring and the groove in certain positions of a cycle, for the pressure is lower in the last room.

(c) Case of combined rings with different degrees of air tightness

Using two rings with different air tightness, we tried to compare the calculation and experiment in the value. In Fig. 8, the curves show calculated values that represent connections of equivalent leakage values, and dots are measured values. It is known that if the ring with poor tightness and the right ring are used together at the same time, the former makes hardly any contribution to the air tightness.

(d) The volume between two rings and leakage

It is supposed from Eq. (5) that if volume \(V\) is spread out, the pressure drops in it, and the gas leakage decreases too. So using 2 rings, we studied the relation between the gas leakage and \(V\) as \(V = 0.34 \times 10^{-6}\) m\(^3\), \(2.86 \times 10^{-6}\) m\(^3\) and \(5.34 \times 10^{-6}\) m\(^3\). Fig. 9 shows an example of calculated results of a pressure drop in the case of increased \(V\). This pressure drop is due to the unsteady effect of the pressure fluctuation, and its effect can be seen clearly in Fig. 10 which shows the values of measurements and calculations. The drop of gas leakage is a little, but it is due to the contact of lower surface of the
2nd ring and the surface of groove being deteriorated, because the pressure drop is large in this room, as seen from Fig. 9. This matter was substantiated in the following way, i.e. when the 2nd ring groove was spread, a spring was set between the surface of groove and the upper surface of the ring, then the measurement was tried, and its results almost corresponded to the calculated results as shown with × mark in Fig. 10.

Further this unsteadiness gives an interesting effect as stated in the following. Fig. 11 shows comparison of amounts of leakage when the number of rings was changed and when V was changed with 2 rings retained. In the case when retaining \( V = 0.34 \times 10^{-4} \text{m}^3 \), we increase the number of rings from 2 to 3, and secondly in the case when we spread \( V \) from \( 0.34 \times 10^{-4} \text{m}^3 \) to \( 1.8 \times 10^{-4} \text{m}^3 \) and increase that of the ring from 2 to 4, thirdly in the case when we...
spread \( V \) from \( 0.34 \times 10^{-6} \text{ m}^3 \) to \( 3.6 \times 10^{-6} \text{ m}^3 \) with 2 rings, the effect for gas leakage is equal. Therefore in the case of spreading of \( V \) there is no rise of friction that would happen in the case of an increase of the number of rings. This effect is more conspicuous in the case of a high speed engine.

(e) Revolution and leakage Fig. 12 shows that the distribution of pressure in each room and the quantity of leaking gas which are calculated with the same indicator diagram, changing the revolution of crank shaft. The more the revolution is increased, the more the effect of unsteadiness increases, so the quantity of gas leakage becomes the lower.

4-3 The consistency of combustion gas in the leaking gas

Figs. 13 (a) and (b) show the calculated results of consistency of combustion gas in each room. In the indicator diagram of the engine used, the combustion began at about \( 5^\circ \) after T.D.C. and its pressure became maximum at about \( 10^\circ \) after T.D.C., so in the latter half of the cycle the combustion gas was contained in the leaking gas, but as seen from these figures its consistency was very small due to the effect of flowing backward caused through unsteadiness, and then the ratio of CO\(_2\) in the exhaust gas of this engine was about 8% under these calculating condi-
tions, and the consistency of CO₂ in the gas leaking into the crank case became very low as shown with dotted line, its consistency per one cycle was about 0.19% in the case of Fig. 13 (a) and about 0.35% in the case of Fig. 13 (b). This explains the cause of the combustion gas being little in the leaking gas.

4-4 General character of gas leakage

Common character of gas leakage will be shown by the following examples of calculations. Figs. 14 (a), (b) and (c) show the distribution of pressure, difference of pressure within each room and the process of gas leakage from room to room, when the engine is used, having 2 H.P. at 800 r.p.m. and 3 rings with \( f = 0.142 \times 10^{-6} \text{ m}^3 \). As showing Figs. 14 (a) and (b), after point A where the pressure of inside of the 1st room becomes equal to that in the combustion chamber, the 1st ring does not make any contribution to air tightness, further than point B, 2nd ring does neither and 3rd ring works alone. And from Fig. 14 (c), total quantity of gas which flows from one room to other room is equal to the amount of gas which leaks to crank case, but the process of its flow is different, especially in the latter half of cycle; the gas flows back to the combustion chamber. Therefore in discussion on the gas flow through the ring section, it is not proper to think that there is a unit orifice in the combustion chamber and the gas flows through it \( \Theta \), except in the case of discussion on the tendency of it.

5. Conclusions

From above studies, the following results are obtained.

(1) The calculated results and the experimental values are consistent with each other, and it was proved that the assumptions for gas flow in this study and the calculating method were proper.

(2) The mechanism of gas leakage through the piston rings corresponds to that of the gas flowing through the labyrinth, changing rapidly its properties, especially it is characteristic that the unsteadiness has a large effect on the air tightness of the ring.

(3) Therefore the gas flow through the ring sections is more complicated than that through the unit orifice.

(4) It is proved that the leaking gas hardly contains the combustion gas owing to the unsteadiness of it.

(5) To decrease the quantity of leaking gas through the rings, it is necessary that the air tightness of each ring is increased; the combinations of rings are well studied, and a small number of good air tight rings should be combined effectively.

References

(1) S. Furuhama and T. Tada: This Bulletin, p. 684.
(3) M. Eweis: Forsch.-h. 371 (1935).