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Vacuum Sealing with a Spiral Grooved Gas Dynamic Seal

(Experimental Performance and New Sealing Coefficient

for the Extremely Low Pressure Range)*

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Sealing performance of gas dynamic seals with rectangular spiral grooves is studied experimentally for the purpose of comparison with the theory previously reported by Sawada. Systematic experiments are made for several seals with various geometries over a wide pressure range from the free molecule to slip flow regimes.

A new sealing coefficient for the extremely low pressure range which is based on pressure ratio is proposed and is calculated under the condition of a free molecule flow.

Suggestions are made regarding the optimum configurations for the rarefied gas dynamic seal.

Key words: Machine Element, Vacuum Sealing, Spiral Grooved Seal, Slip Flow, Free Molecule Flow.

1. Introduction

In recent years, the necessity of non-contact seals without liquid sealant has increased for the purpose of sealing between two vacuum spaces or between a vacuum and an atmospheric space, for instance, vacuum holding around rotors of centrifuges for uranium enrichment, shaft sealing of molecular pumps, etc. Consequently, spiral grooved gas dynamic seals have attracted special interest.

The senior author of this paper⁽¹⁾ previously obtained the sealing coefficient theoretically taking account of side wall effects and density change effects on the assumption of a slip flow condition. These theoretical results were compared with the experimental data of Baron⁽²⁾, King⁽³⁾ and Milligan et al.⁽⁴⁾, and the validity of the theory was confirmed. But, these experiments are not enough for detailed discussion of the pressure range where the theory is applicable, because some of these works do not give geometrical dimensions of seals in detail and others do not describe experimental conditions sufficiently. In their paper, Milligan et al. give a fairly detailed descriptions of experimental conditions. But, since two or more geometrical parameters are changed simultaneously in their experiments, their results are useless to investigate the effects of geometrical dimensions on the sealing performance.

In this paper, for the purpose of detailed comparison between the experiment and the theory, systematic experiments for several seals with various geometries are made over a wide pressure range from the free molecule to slip flow regimes. Since the conventional sealing coefficient becomes a function of pressure in a low pressure range, a new sealing coefficient which does not depend on the pressure in a low pressure range is proposed, and is calculated under the condition of a free molecule flow. The calculated results are compared with the experimental ones.

2. Experiment

2.1 Experimental apparatus and procedure

Figure 1 is a cross-sectional view of the experimental apparatus, which consists of a vacuum chamber ①, a high frequency induction motor ② in the chamber and a spiral grooved seal ③ directly mounted on the motor shaft. The vacuum chamber is connected to a pumping system composed of a mercury diffusion pump and an oil rotary pump through a throttling valve. In order to avoid the influence of outgassing from the inside of the motor on the experiments in a low pressure range, the back of the motor is also connected to the vacuum pump. Spiral grooved seals are made of a high strength aluminum alloy. Figure 2 is a photograph of seals, and the details of their geometrical dimensions are given in Fig. 3 and Table 1. Rotational speed of a seal is changeable from about 50 to 300 s⁻¹. Radial clearance between a seal and a sleeve is 0.2 mm, and the total amount of eccentricity, cylindrical error and out-of-roundness are less than 10 μ m. Radial expansion due to both centrifugal force and temperature rise is less than 5 μ m. These effects on

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Fig. 1 Cross-sectional view of experimental apparatus

Fig. 2 Photograph of seals

Fig. 3 Details of seal

Table 1 Geometrical dimensions of seal

Seal number	Helix angle α°	Groove width a mm	Ridge width d mm	Groove depth h mm	Number of grooves	Aspect ratio $\xi = a/b$	Clearance parameter $\beta = b/\delta$	Groove width ratio $\epsilon = a/(a+d)$
1	14.28	2.0	2.07	1.0	10	1.667	6.0	0.491
2	14.28	1.0	0.94	1.0	20	0.833	6.0	0.516
3	14.28	4.0	3.75	1.0	5	3.333	6.0	0.516
4	14.28	4.0	3.75	2.0	5	1.818	11.0	0.516
5	7.26	2.0	1.96	1.0	5	1.667	6.0	0.504
6	7.26	4.0	5.92	2.0	2	1.818	11.0	0.403

the radial clearance can therefore be neglected. Before the experiments, the vacuum chamber was evacuated sufficiently and the ultimate pressure of 6.7×10^{-2} Pa (5×10^{-4} Torr) was reached. The pressure in the chamber was maintained in the range of $13.3 \sim 2.7 \times 10^4$ Pa ($10^{-1} \sim 200$ Torr) [for helium $\sim 6.7 \times 10^4$ Pa (~ 500 Torr)] by admitting a test gas into the downstream side of a seal. Then keeping the rotational speed at 50~55, 100~102, 200~202 or 300~302 s^{-1} (corresponding peripheral speed is 7.9~8.6, 15.7~16.1, 31.4~31.7 or 47.1~47.4 m/s), the upstream pressure and the pressure dif-

ference between the upstream and downstream sides were measured. Upstream pressures less than 1.3×10^3 Pa (10 Torr) were measured with a Baratron vacuum transducer (Type 222, manufactured by MKS Instruments Inc.), whose lowest measurable pressure was 1.3×10^{-1} Pa (10^{-3} Torr) and the shift of zero point against $1^\circ C$ was around 0.8 Pa (6×10^{-3} Torr). But often adjustment of zero point suppresses the shift to less than 1.3×10^{-1} Pa (10^{-3} Torr). Upstream pressures from 1.3×10^3 to 2.7×10^4 Pa (10 to 200 Torr) were measured with a diaphragm vacuum gauge (Type GD-B2, manufactured by ULVAC Corp.),

which was easily affected by the temperature change and an error of several hundreds of Pa's was expected. For the measurement of pressure difference in a relatively high pressure range where large pressure differences occurred, an inclined oil manometer was used, and in a low pressure range where the pressure difference was small, a differential precision manometer (Model ISP-3, manufactured by Shibata Chemical App. Mfg. Co.) was used. The total error of both inclined angle and reading of the scale with the oil manometer was less than 15 Pa (0.11 Torr), the accuracy of ISP-3 was better than 0.2 Pa (1.5×10^{-3} Torr) and the zero shift during a couple of hours was less than 0.3 Pa (2.2×10^{-3} Torr). In order to investigate the difference in sealing performance with species of gases, experiments were made with three gases i. e., helium, nitrogen and argon.

2.2 Experimental results

Measured pressure differences are plotted against the downstream pressures in Fig. 4. Solid curves in the figure are theoretical results of a previous paper⁽¹⁾, and they are in good agreement over the whole experimental pressure range. Measured values are a little smaller than theoretical ones for the case of high pressure and high rotational speed (high peripheral speed). This point is still left as a subject of future study. In this paper, the authors' interest is directed to the performance in a low pressure range.

Using the following equation which defines the average sealing coefficient, plots in Fig. 4 are rearranged in Fig. 5.

$$\Lambda = \frac{6\mu U}{\delta^2} \frac{\Delta p}{L} \quad \dots\dots\dots (1)$$

where μ is the viscosity, U the peripheral

speed, L the total seal length, δ the radial clearance and Δp the pressure difference.

The abscissa in Fig. 5 shows the inverse Knudsen number ($1/K_n = \delta/\lambda$, λ : mean free path) based on the downstream pressure and the radial clearance. The average sealing coefficient for large inverse Knudsen numbers is independent of either pressure or rotational speed as shown in Fig. 5. This means that since the pressure gradient $(d\bar{p}/dl)_{Q=0}$ does not depend on the pressure, the approximation that $(d\bar{p}/dl)_{Q=0} \approx \Delta p/L$ holds fairly well. But, when the pressure decreases and thus the inverse Knudsen number is under 10, the local sealing coefficient begins to change with the pressure as shown in Fig. 5 with a broken curve. Therefore, if the downstream pressure is kept constant, the upstream pressure changes with the rotational speed, and therefore the average value of the sealing coefficient changes with the rotational speed. Solid curves in the figure show theoretical results calculated in the way proposed in the previous paper. Experimental results for all the rotational speeds agree well with the calculated ones for inverse Knudsen numbers above 5. Similar experimental results were acquired for each seal shown in Table 1, and for three gases He, N_2 and A. These results are rearranged in Fig. 6, and the influence of geometrical parameters (aspect ratio, helix angle and clearance parameter), rotational speed and species of gases on the sealing coefficient is examined.

Figure 6 (a) shows the sealing coefficient plotted against the aspect ratio. Results for seals No. 1, No. 2, No. 3, which are different only in the aspect ratio from one another and are almost the same in all other geometries, are shown in this figure. The average sealing coefficient Λ_m is

1 Pa = 7.50×10^{-3} Torr

Fig. 4 Pressure difference

Fig. 5 Sealing coefficient

Fig. 6 Sealing coefficient
[Influence of geometrical parameters,
rotational speed and species of gases]

likely to decrease as the aspect ratio increases, but when the aspect ratio is above 2, Λ_m does not change remarkably. For Knudsen numbers of 0.1 and 0.01, the experimental results agree well with the theoretical ones and for a Knudsen number of 1, they tend to agree with each other, but the experimental results are a little larger than the theoretical ones. Figure 6 (b) shows the results for seals different in the helix angle. Two cases where clearance parameter $\beta=6$ and where $\beta=11$ are shown in the figure. When $\beta=11$, the sealing coefficient Λ_m increases rapidly with an increase in helix angle α , but when $\beta=6$, Λ_m is not much affected by α . Figure 6 (c) shows the results for seals No. 1 and No. 4 which are different in the clearance parameter from each other. Seal No. 1 which has a smaller clearance parameter than No. 4 gives a smaller sealing coefficient. Figure 6 (d) shows the relationship between the average sealing coefficient and the peripheral speed. For the cases of $K_n=0.01$ and 0.1, the sealing coefficient Λ_m is independent of the peripheral speed and is almost constant, but Λ_m increases exponentially with the peripheral speed for the case of $K_n=1$. Figure 6 (e) shows the experimental results for three gases He, N_2 and A plotted against the molecular weight. It is found that the average sealing coefficient is independent of the molecular weight for low rotational speeds, but as the rotational speed increases and also the Knudsen number increases, the average sealing coefficient increases with the molecular weight.

All the experimental performances described above are in good agreement with the theoretically predicted ones. From these experimental results, the proposal for the optimum geometrical parameters (i. e., aspect ratio $\xi \approx 2$, helix angle $\alpha = 15^\circ$ and clearance parameter $\beta = 3 \sim 5$) in the previous paper is confirmed. But as described in the previous paper, the sealing coefficient defined by eq. (1) fails to estimate the sealing performance in a low pressure range. For instance, if the downstream pressures of two seals are kept at the same value 10^5 Pa (7.5 Torr) and one of them attains the upstream pressure of 10 Pa (7.5×10^{-2} Torr) and the other 1 Pa (7.5×10^{-3} Torr), the pressure difference Δp for either seal will be almost the same. Consequently, eq. (1) is supposed to give almost the same value for both seals. It is found unfavourable to give an illusion that the sealing performances of these two seals are same, and that the sealing performance gets worse as the rotational speed increases and the upstream pressure decreases as is shown in Fig. 6 (d).

The sealing coefficient is defined essentially as a measure for judging the propriety of geometrical dimensions and it is also defined to be independent of pressure and peripheral speed near the atmospheric pressure. But in a low pressure range where the inverse Knudsen number is below $10 \sim 20$, the sealing coefficient becomes a function of both pressure and

Fig. 7 Groove (Illustration of symbols)

peripheral speed. Therefore, an improved sealing coefficient for the extremely low pressure range is now proposed.

3. Sealing coefficient for the extremely low pressure range

3.1 Theory

It is desirable that a new sealing coefficient take a constant value in a low pressure range and be therefore independent of pressure, peripheral speed and species of gases if possible. Furthermore, it ought to be a quantity which makes it possible to estimate the propriety of geometrical dimensions. The momentum which gas molecules give up to the wall-pieces of length dy per unit time must be equated to the difference in force exerted on the two cross-sections of the groove separated by distance dy by a difference in pressures $(\partial p / \partial y)_g dy$ (see Fig. 7). In the extremely low pressure range, the flow in a seal is supposed to be a free molecule flow. Consequently, the following equation holds.

$$\frac{3}{8} \sqrt{\frac{\pi}{2}} \rho \sqrt{\frac{p}{\mu}} \{2v(a+b-\delta) - Va\} dy = -A \left(\frac{\partial p}{\partial y} \right)_g dy \quad (2)$$

where V is the velocity component of the moving wall along the groove, v the mass velocity of gas along the groove and A the cross-sectional area of the groove ($=ab$). Then, the volume flow rate per unit groove width is obtained from eq. (2) as follows:

$$q = \frac{Av}{a} = \frac{1}{2} \frac{A}{a+b-\delta} V - \frac{4}{3\sqrt{\pi}} \frac{1}{\rho} \sqrt{\frac{p}{\mu}} \frac{bA}{a+b-\delta} \left(\frac{\partial p}{\partial y} \right)_g \quad (3)$$

If the volume flow rate q is divided into two parts, i. e., q_g through the cross-section (I) and q_δ through the cross-section (II) (see Fig. 7), the following equations are obtained.

$$\left. \begin{aligned} q_g &= \frac{b-\delta}{b} q = q_v b V + q_p \frac{b^3}{2\mu} \left(\frac{\partial p}{\partial y} \right)_g \\ q_\delta &= \frac{\delta}{b} q = q'_v b V + q'_p \frac{b^3}{2\mu} \left(\frac{\partial p}{\partial y} \right)_g \end{aligned} \right\} \quad (4)$$

Here, introducing nondimensional variables $\xi = a/b$ (aspect ratio), $\beta = b/\delta$ (clearance parameter) and $K_n = \lambda/\delta$ (Knudsen number), q_v , q'_v , q_p and q'_p are given by

$$\left. \begin{aligned} q_v &= \frac{1}{2\beta(1+\xi)-1} \cdot q_p = -\frac{16}{3\pi\beta^2(1+\xi)-\beta} K_n \\ q'_v &= \frac{1}{2\beta(1+\xi)-1} \cdot q'_p = -\frac{16}{3\pi\beta^2(1+\xi)-\beta} K_n \end{aligned} \right\} \quad (5)$$

Similarly, in the ridge region, the following relationship holds between the mass velocity of gas parallel to the groove v_r and the pressure gradient $(\partial p / \partial y)_r$ by momentum theorem.

$$\frac{3}{8} \sqrt{\frac{\pi}{2}} \rho \sqrt{\frac{p}{\rho}} \{2v_r d - Vd\} dy = -A \left(\frac{\partial p}{\partial y} \right)_r dy \quad (6)$$

Then the volume flow rate per unit ridge width q_r is obtained from eq. (6).

$$q_r = v_r d = \frac{1}{2} d V - \frac{16}{3\pi} K_n d^3 \left(\frac{\partial p}{\partial y} \right)_r \quad (7)$$

If eq. (7) is rewritten in the form

$$q_r = r_v b V + r_p \frac{b^3}{2\mu} \left(\frac{\partial p}{\partial y} \right)_r \quad (8)$$

r_v and r_p in eq. (8) are written as

$$r_v = \frac{1}{2\beta} \cdot r_p = -\frac{16}{3\pi} \frac{K_n}{\beta^3} \Omega \quad (9)$$

where Ω is a correction factor which must be taken into account when d/δ is small⁽⁵⁾. Introducing $\hat{q}_p = q_p/K_n$, $\hat{q}'_p = q'_p/K_n$ and $\hat{r}_p = r_p/K_n$, the conventional sealing coefficient Λ [eq. (21) in reference (1)] is given by

$$\Lambda = \frac{\left[-3\beta \{ (1-\varepsilon) \hat{q}_p (\hat{q}_p + \hat{q}'_p) \sin^2 \alpha + \hat{r}_p \{ \varepsilon \hat{q}_p \sin^2 \alpha + \hat{q}'_p \{ 1/\varepsilon - 2(1-\varepsilon) \sin^2 \alpha \} + (1-\varepsilon) \beta^2 \sin^2 \alpha \} \right]}{\left[(1-\varepsilon) \cos \alpha \sin \alpha \{ \hat{q}_p (q_v + q'_v - r_v) + \hat{r}_p \{ \varepsilon q_v / (1-\varepsilon) - q'_v + r_v \} \right]} K_n \quad (10)$$

Since the contents in the large brackets on the right hand side of eq. (10) are functions only of geometrical dimensions, they can be expressed as $f(\xi, \alpha, \beta, \varepsilon)$. Now defining

the sealing coefficient for the extremely low pressure range as follows:

$$\Lambda_r = \frac{\Lambda}{K_n} = f(\xi, \alpha, \beta, \varepsilon) \quad (11)$$

Λ_r depends only on the geometrical dimensions. On the other hand, since the conventional sealing coefficient Λ is defined as follows⁽¹⁾:

$$\Lambda = \frac{6\mu U}{d^2 (d\bar{p}/dl)_{Q=0}} \quad (12)$$

then, Λ_r is written as

$$\Lambda_r = \frac{6\mu U}{d^2 (d\bar{p}/dl)_{Q=0}} \frac{1}{K_n} \quad (13)$$

Let ρ be the density, $\bar{c}$ the mean velocity of molecules and λ the mean free path. Then, the viscosity μ is written as $\mu = 0.499 \rho \bar{c} \lambda$ ⁽⁶⁾. Consequently, the inverse Knudsen number $1/K_n$ can be transformed in the following way.

$$\frac{1}{K_n} = \frac{\delta}{\lambda} = 0.499 \sqrt{\frac{8M}{\pi RT}} \frac{\rho \delta}{\mu} \approx \frac{2}{\sqrt{\pi}} \sqrt{\frac{M}{2RT}} \frac{\rho \delta}{\mu} \quad (14)$$

where R is the universal gas constant, T the absolute temperature and M the molecular weight. Substituting eq. (14) into eq. (13), Λ_r is rewritten as

$$\Lambda_r = \frac{12}{\sqrt{\pi}} \frac{U}{\sqrt{2RT/M}} \frac{1}{d^2 d(\log \bar{p})/dl} \quad (15)$$

Noting that $\sqrt{2RT/M}$ is the most probable velocity and introducing the nondimensional peripheral speed $\hat{U} = U/\sqrt{2RT/M}$ and the nondimensional seal length $\hat{L} = L/d$, the average value of Λ_r over the total seal length is presented as

$$\Lambda_{rm} = \frac{12 \hat{U} \hat{L}}{\sqrt{\pi} \log(p_2/p_1)} \quad (16)$$

Fig. 8 New sealing coefficient

3.2 Comparisons of theoretical and experimental results

Experimental results of Λ_{rm} plotted against the inverse Knudsen number based on the downstream pressure are shown in Fig. 8. Curves shown in the right part of the figure are theoretical results obtained by assuming a slip flow condition in the seal. They are in good agreement with the experimental results for $1/K_n \geq 5$ and the discrepancy between these curves and the experimental results becomes larger as $1/K_n$ decreases below 5. Therefore, the lower limit of inverse Knudsen number where the slip flow theory is applicable is presumably 5 or so. A dot-chain line drawn in the left part of the figure indicates the theoretical results for the free molecule flow condition [eq. (10)]. They agree well with the experimental results in a low pressure range. This new sealing coefficient is independent of peripheral speed and species of gases, but depends only on the geometrical parameters (i. e., aspect ratio, clearance parameter and helix angle). Thus it is verified that this new sealing coefficient is suitable as a measure for estimating the sealing performance in a low pressure range. Since the similar experimental results were obtained for each seal shown in Table 1, the results in the free molecule flow range (for inverse Knudsen numbers below 0.1) are plotted against geometrical parameters in Fig. 9. A few experimental results differ a little from theoretical curves. This is because values d/δ for those seals are small. If the correction factor Ω for r_p is properly used in the calculation, the theoretical results approach the experimental ones.

3.3 Determination of the optimum configurations

Since the validity of the theory has been confirmed from the above results, let

us now observe the relationship between the sealing coefficient and the geometrical dimensions, and then discuss the optimum configurations. Differentiating eq. (11) with respect to α and setting $\partial \Lambda_{rm} / \partial \alpha$ at zero, the optimum helix angle α_{op} is obtained as follows:

$$\alpha_{op} = \tan^{-1} \left[\frac{\hat{r}_p \hat{q}_p / \epsilon}{\left[(1-\epsilon) \hat{q}_p (\hat{q}_p + \hat{q}_p') + \hat{r}_p \{ \epsilon \hat{q}_p - 2(1-\epsilon) \hat{q}_p' \} + \hat{q}_p' / \epsilon \right] + \hat{r}_p^2 (1-\epsilon)} \right]^{\frac{1}{2}} \quad (17)$$

The sealing coefficient Λ_{ro} for α_{op} is given by

$$\Lambda_{ro} = \frac{6\eta^2 \left[(1-\epsilon) \hat{q}_p (\hat{q}_p + \hat{q}_p') + \hat{r}_p \{ \epsilon \hat{q}_p - 2(1-\epsilon) \hat{q}_p' \} + \hat{q}_p' / \epsilon \right]^{\frac{1}{2}} \left[\frac{\hat{q}_p \hat{r}_p}{\epsilon} \right]^{\frac{1}{2}}}{\left[(1-\epsilon) \{ \hat{q}_p (q_v + q_v' - r_v) + \hat{r}_p \{ \epsilon q_v / (1-\epsilon) - q_v' + r_v \} \right]} \quad (18)$$

The calculated results of eqs. (17) and (18) are shown in Fig. 10. It is found in Fig. 10 (a) that a smaller helix angle is desirable for a larger aspect ratio and that a larger aspect ratio is better, but if the aspect ratio is larger than 2, its influence on the sealing performance is not remarkable. It is found in Fig. 10 (b) that a smaller helix angle is suitable for a larger clearance parameter and that if the optimum helix angle α_{op} is chosen, the sealing coefficient is maintained almost constant for a clearance parameter larger than 10. It is also found in Fig. 10 (c) that Λ_{rm} takes the minimum value if the groove width ratio ϵ is near 0.5, but ϵ has little influence as far as it is not extremely smaller than 0.5.

Judging from all these facts, the aspect ratio $\xi \geq 2$, helix angle $\alpha = 15^\circ$, clearance parameter $\beta = 7 \sim 10$ and groove width

Fig. 9 New sealing coefficient
(Influence of geometrical parameters)

Fig. 10 Optimum values of helix angle and corresponding new sealing coefficient

ratio $\epsilon=0.4 \sim 0.6$ can be recommended for the optimum configurations of a rarefied gas dynamic seal. Comparing the above values with those in a relatively high pressure range where slip flow conditions hold, it is found that the aspect ratio, helix angle and groove width ratio are all similar to those for the slip flow condition, but the clearance parameter takes a little larger values. Therefore, it is concluded that spiral grooves must be made a little deeper as the pressure decreases.

4. Conclusions

Experiments have been made over a wide pressure range from the free molecule to slip flow regimes in order to confirm the validity of a theory previously reported by one of the author (T. Sawada), and also to determine the pressure range where the theory is applicable. It has been pointed out that the conventional sealing coefficient does not provide a proper estimation for the sealing performance in the extremely low pressure range and then a new sealing coefficient has been proposed.

The conclusions are summarized as follows:

(1) The theory based on the slip flow condition is applicable in a pressure range of $1/K_n \geq 5$.

(2) The conventional sealing coefficient in a relatively high pressure range is independent of pressure values. Therefore, the sealing performance is correctly estimated by the conventional sealing coefficient in a relatively high pressure range ($1/K_n \geq 10$).

(3) The sealing performance in the pressure range of $1/K_n \leq 1$ can be estimated by a new sealing coefficient which is based on the pressure ratio.

(4) In the range of $1 < K_n < 10$, it is difficult for both sealing coefficients described above to give an estimate of the sealing performance.

(5) The following values are recommended for geometrical parameters in the extremely low pressure range where the free molecule flow holds: Aspect ratio $\xi \geq 2$, helix angle $\alpha = 15^\circ$, clearance parameter $\beta = 7 \sim 10$ and groove width ratio $\epsilon = 0.4 \sim 0.6$.

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