1st International Global on Renewable Energy and Development (IGRED 2017) IOP Publishing
IOP Conf. Series: Earth and Environmental Science **100** (2017) 012123 doi:10.1088/1755-1315/100/1/012123

Effect of the Tangential Momentum Accommodation Coefficient on the Performance of the Spiral Groove Dry Gas Seal

Penggao Zhang[1], Long Wei[2], and Xiu Feng[3]

Fluid Sealing Measurement and Control Engineering Research and Development Center of Jiangsu Province, Nanjing Polytechnic Institute, 210048, Nanjing, China

[1]249954371@163.com, [2]weilong1972@163.com, [3]fxsue@163.com

Abstract. The mean free path of gaseous molecules was revised by introducing the tangential momentum accommodation coefficient. The effective viscosity coefficient equation was deduced. Based on Muijderman narrow groove theory, the performance parameters of gas film were calculated by the trial method for the spiral groove dry gas seal. It has been found that the leakage rate decreases and the opening force of the gas film increases with the increasing of the tangential momentum accommodation coefficient, and both of them change little when the tangential momentum accommodation coefficient is bigger than 0.4. Both of them increase with the increasing of rotating speed and spiral groove angle, and change little when the spiral groove angle is bigger than 20º. The leakage rate increases and the opening force decreases with the increasing of film thickness.

1. Introduction

When the dry gas seal operates at a lower speed, the gap between the rotating ring and the stationary ring is very narrow, and close to the mean free path of the gas molecule, so the slip flow effect of the gas cannot be neglected.

Ruan et al. calculated the performance of dry gas seal at the low speed and the low pressure by using finite element method, and found that slip flow effect of gas is obvious, and cannot be neglected[1]. Xu et al., Wang et al., and Yin et al. revised the Reynold equation by the first order slip flow model built by Burgdorfer, and analyzed the effect of slip flow on the performance of the dry gas seal[2-4]. Zhao et al. solved the Reynold equation based on Fukui slip flow model, and analyzed the performance of the spiral groove gas seal at low speed[5]. Ding et al. solved the Reynold equation revised by the first order slip flow model built by Burgdorfer by the approximately analytical approach[6]. Xu et al. solved the Reynold equation revised by both surface micro-scale slip flow effect and thermal viscosity effect, and analyzed the effect of slip flow effect and thermal viscosity effect on the performance of the dry gas seal[7]. Peng et al. analyzed the performance of the dry gas seal by considering effects of both real gas and slip flow[8].

In this paper, the tangential momentum accommodation coefficient was introduced to revise the mean free path of gaseous molecules, and the effective viscosity coefficient equation of dry gas was deduced. Based on Muijderman narrow groove theory, the performance parameters of the gas film were calculated by the trial method for the spiral groove dry gas seal.

2. Effective viscosity coefficient equation of gas

The macroscopic performance of slip effect is equivalent to the reduction of viscosity, the gas viscosity considering the slip flow effect is called the effective viscosity coefficient, and it built by Burgdorger is

$$\mu_e = \frac{\mu}{1+6K_n} \tag{1}$$

Where μ is dynamic viscosity of gas, and K_n is Knudsen number.

Knudsen number K_n is the ratio of the mean free path, λ, of gaseous molecule to the film thickness, h, of the gas film, and

$$K_n = \frac{\lambda}{h} \tag{2}$$

For the complete gas, the mean free path of the gaseous molecule can be calculated by Ref.[9]

$$\lambda = \frac{\mu}{\rho}\left(\frac{\pi}{2\mathrm{RT}}\right)^{1/2} \tag{3}$$

The tangential momentum accommodation coefficient represents the proportion that occur diffuse reflection after the gaseous molecules enter into the seal gap[3]. According to Refs.[2-4,and 10], the effect of the tangential momentum accommodation coefficient on slip velocity is remarkable, it is introduced to revise the mean free path of gas, and

$$\lambda' = \frac{2-\sigma_v}{\sigma_v}\lambda \tag{4}$$

Where σ_v is the tangential momentum accommodation coefficient.

Substituting Eq.(4) into Eq.(5), the revised mean free path of gaseous molecule can be obtained, and it is

$$\lambda' = \frac{2-\sigma_v}{\sigma_v}\frac{\mu}{\rho}\left(\frac{\pi}{2\mathrm{RT}}\right)^{1/2} \tag{5}$$

The relationship among pressure, density and temperature for the gas is

$$p = \rho RT \tag{6}$$

Where R is gas constant.

Substituting λ in Eq.(2) with λ' in Eq.(5), the revised K_n can be obtained, and

$$K_n = \frac{1}{h}\frac{2-\sigma_v}{\sigma_v}\frac{\mu}{p}\left(\frac{\pi RT}{2}\right)^{1/2} \tag{7}$$

Substituting Eq.(7) into Eq.(1), the effective viscosity coefficient can be obtained, and it is

$$\mu_e = \frac{\mu}{1+6\left(\frac{1}{h}\frac{2-\sigma_v}{\sigma_v}\frac{\mu}{p}\left(\frac{\pi RT}{2}\right)^{1/2}\right)} \tag{8}$$

3. Governing equations of lubricant film pressure

According to the narrow groove theory of Muijderman[11], the governing equations of gas film pressure along the radial of sealing ring are

In the region of sealing dam,

$$\frac{dp}{dr} = \frac{6\mu q_m RT}{\pi h_0^3}\frac{1}{pr} \tag{9}$$

In the region of spiral groove,

$$\frac{dp}{dr}=-\frac{6\mu\omega g_1}{h_0^2}r+\frac{6\mu q_m g_2 RT}{\pi h_0^2 h_1}\frac{1}{pr} \tag{10}$$

Where q_m is the mass flux of gas, kg·s^{-1}. h_0 is the film thickness of gas, m. h_1 is the film thickness in the region of spiral groove, and $h_1=h_0+h_g$, m. h_g is the depth of spiral groove, m. ω is the angular velocity of rotation of seal ring, rad·s^{-1}. g_1 and g_2 are the coefficients of spiral grooves, respectively, and

$$g_1=\frac{\gamma H_1^2\cot\alpha(1-H_1)(1-H_1^3)}{(1+\gamma H_1^3)(\gamma+H_1^3)+H^3\cot^2\alpha(1+\gamma)^2},\quad g_2=\frac{(1+\gamma)H_1^2(1+\cot^2\alpha)(\gamma+H_1^3)}{(1+\gamma H_1^3)(\gamma+H_1^3)+H_1^3\cot^2\alpha(1+\gamma)^2}$$

Where α is the angle of spiral groove, °. γ is the ratio of width of groove to weir. H_1 is the ratio of the film thickness in the sealing dam to spiral groove, and $H_1=\frac{h_0}{h_0+h_g}$.

Substituting the effective viscosity coefficient μ_e in the Eq.(8) into dynamic viscosity μ in the Eqs.(9) and (10). The gas film pressure governing equation revised by tangential-momentum-accommodation coefficient can be obtained.

In the region of sealing dam,

$$\frac{dp}{dr}=\frac{6q_m RT}{\pi h_0^3}\frac{\mu}{1+6\left(\frac{1}{h}\frac{2-\sigma_v}{\sigma_v}\frac{\mu}{p}\left(\frac{\pi RT}{2}\right)^{1/2}\right)}\frac{1}{pr} \tag{11}$$

In the region of spiral groove,

$$\frac{dp}{dr}=-\frac{6\omega g_1 r}{h_0^2}\frac{\mu}{1+6\left(\frac{1}{h}\frac{2-\sigma_v}{\sigma_v}\frac{\mu}{p}\left(\frac{\pi RT}{2}\right)^{1/2}\right)}+\frac{6q_m g_2 RT}{\pi h_0^2 h_1}\frac{\mu}{1+6\left(\frac{1}{h}\frac{2-\sigma_v}{\sigma_v}\frac{\mu}{p}\left(\frac{\pi RT}{2}\right)^{1/2}\right)}\frac{1}{pr} \tag{12}$$

4. Solution of governing equations

The boundary conditions of Eq.(11) and (12) are $p|_{r=r_i}=p_i$ at the inner diameter and $p|_{r=r_0}=p_0$ at the outer diameter of sealing ring.

According to Song, et al. [12], the solving approach is that the mass flux of gas flowing through the sealing dam is equal to the mass flux flowing through the region of spiral groove according to the law of conservation of mass. Assuming the mass flux q_m, the gas pressure, p_g, at the root of spiral groove was calculated according to $p|_{r=r_i}=p_i$ and Eq.(11), and the gas pressure distribution, $p(r)$, from r_i to r_g was obtained at the same time. Substituting p_g into Eq.(12), the gas pressure distribution, $p(r)$, from r_g to r_0 was obtained, and $p(r_0)$ was obtained. If $p(r_0)=p_0$, $p(r)$ was the pressure distribution between end faces. If not, the mass flux q_m was assumed again, the trial procedure was repeated until $p(r_0)=p_0$.

5. Results analysis and discussion

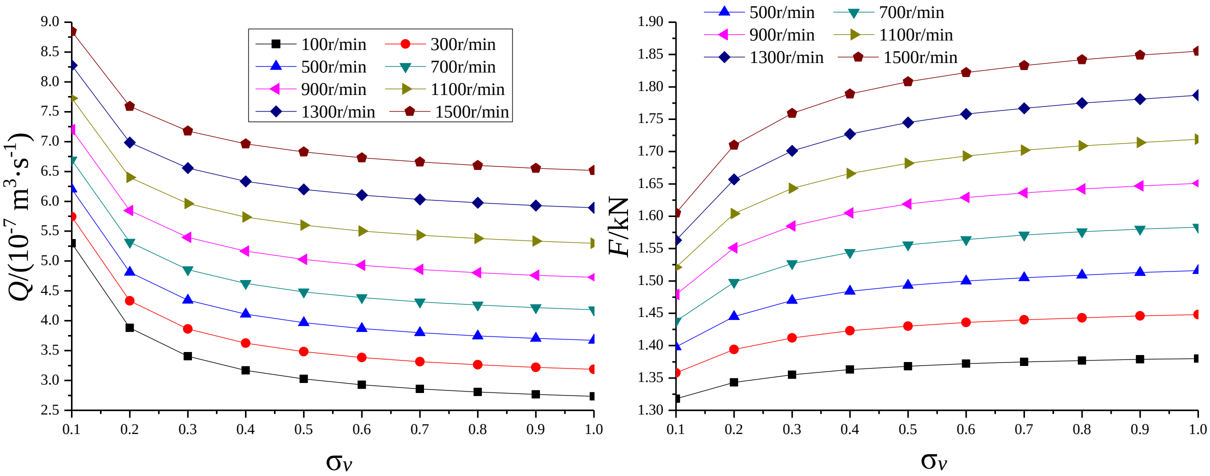
5.1. Example

The parameters of mechanical seal are r_i=30mm， r_g=34.8mm, r_0=42mm, h_g=2.5μm, h_0=1μm, γ=1, and α=20°. The medium is air, μ=1.79╳10^{-5}Pa·s, R=287J/kg·K, T=300K, p_i=0.6MPa, p_0=0.1MPa.

5.2. Results and discussions

5.2.1. Effects of σ_v and ω on the performance of dry gas seal

The effects of σ_v and ω on the performance of dry gas seal are shown in Figure 1. It can be seen that the leakage rate, Q, decreases and the opening force, F, of the dry gas film increases with the increasing of the tangential momentum accommodation coefficient σ_v, and both of them increase with the increasing of rotating speed ω. Q and F change little when σ_v>0.4.



(a) Effect of σ_v and ω on Q (b) Effect of σ_v and ω on F

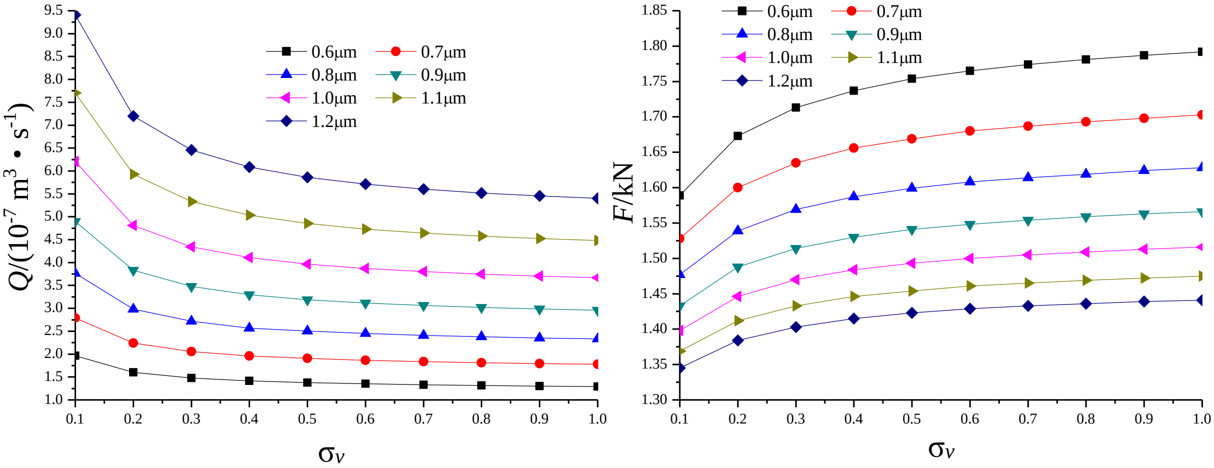
Figure 1. Effects of σ_v and ω on the performance of dry gas seal

The increasing of σ_v means the number of molecules occur diffuse reflection increases, which makes the wall shear stress of gas increase. The momentum loss lost in the wall of incident molecules increases, and therefore Q decreases. Thus, a large number of molecules are accumulated between the end faces, and which makes the opening fore of gas increase.

With the increasing of ω, the centrifugal force of gas increases, and which makes both of Q and F increase.

5.2.2. Effects of σ_v and h_0 on the performance of dry gas seal

The effects of σ_v and h_0 on the performance of dry gas seal when ω=500r/min are shown in Figure 2. It can be seen that Q decreases and F increases with the increasing of σ_v, and Q increases and F decreases with the increasing of film thickness h_0. The smaller h_0 makes the leakage channel become narrow, which makes Q become small. However, the smaller h_0 makes a big number of gaseous molecules accumulate as well, which makes F become larger. It can also be seen that Q and F change little when σ_v>0.4.

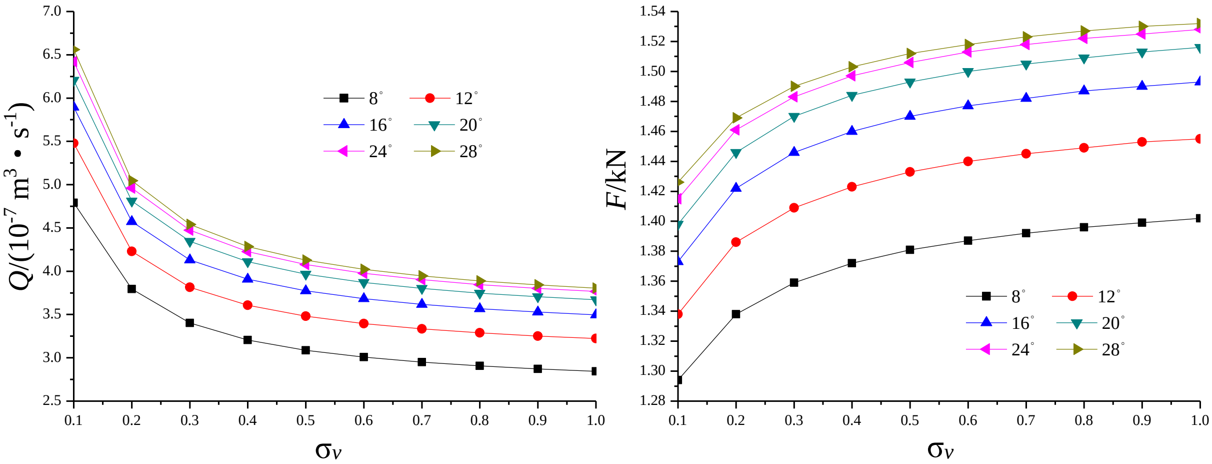


(a) Effect of σ_v and h_0 on Q (b) Effect of σ_v and h_0 on F

Figure 2. Effects of σ_v and h_0 on the performance of dry gas seal

5.2.3. Effects of σ_v and α on the performance of dry gas seal

The effects of σ_v and α on the performance of dry gas seal when ω=500r/min are shown in Figure 3. It can be seen that Q decreases and F increases with the increasing of σ_v, and Q and F increase with the increasing of α. With the increasing of α, the pumping effect of spiral groove increases gradually, which makes the pressure between end faces increase gradually and makes the accumulating effect of gaseous molecules increase. Therefore, Q and F of gas film increase, and larger pressure makes the leakage rate and opening force larger. It can also be seen that the changing amplitudes of Q and F decrease when α>20º and σ_v>0.4.



(a) Effect of σ_v and α on Q (c)Effect of σ_v and α on F

Figure 3. Effects of σ_v and α on the performance of dry gas seal

6. Conclusions

(1) The mean free path of gaseous molecules was revised by introducing of the tangential momentum accommodation coefficient. The effective viscosity coefficient equation was deduced. Based on Muijderman narrow groove theory, the performance parameters of gas film were calculated by the trial method for the spiral groove dry gas seal.

(2) It has been found that Q decreases and F of the dry gas increases with the increasing of σ_v, and both of them change little when σ_v is bigger than 0.4. Both of them increase with the increasing of ω and α, and change little when α is bigger than 20º. The Q increases and F decreases with the increasing of h_0.

Acknowledgments

This work is supported by the Natural Science Foundation of the Jiangsu Higher Education Institutions (17KJB530007) and the 5th "333" High-Level Talents Cultivation Project of Jiangsu Province (BRA2017482).

References

[1] RUAN B 2000 Finite element analysis of the spiral groove gas face at the low speed and the low pressure condition-slip flow consideration *J. Tribology Transactions*, 43 (3), pp. 411-418.
[2] Xu J., Gu C.G., Wang T. 2004 Numerical analysis of gaseous flow in micro-channels *J. Journal of shanghai jiaotong university*, 38(10), pp.1695-1698.
[3] Wang T., Xu J., Gu C.G. 2004 The micro scale effects on the performance of spiral groove gas seal *J. Journal of engineering thermophysics*, 25 suppl, pp.39-42.
[4] Yin X.N. and Peng X.D. 2006 Finite element analysis of a dry gas seal under slip flow conditions *J. Lubrication Engineering*, (4), pp. 55-56.
[5] Zhao Y., Song P.Y, Li W., et al. 2005 The operation characteristics of spiral groove gas face seal at the slowspeed-Theory analysis *J. Lubrication Engineering*, (5), pp.70-73.
[6] Ding X.X, Chen D.L., Zhang W.Z., et al. 2007 An approximately calculation of the micro-scale effect flow field of a spiral groove dry gas seal and parameter optimization *J. Chinese Journal of Applied Mechanics*, 24(3), pp.425 -428.
[7] Xu J., Peng X.D., Bai S.X., et al. 2013 Effects of surface micro-scale and thermal viscosity on sealing performance of spiral-grooved dry gas seal *J. CIESC Journal*, 64(9), pp.3291-3300.
[8] Song P.Y., Zhang S., and Xu H.J. 2016 Analysis of performance of spiral groove dry gas seal considered effects of both real gas and slip flow *J. CIESC Journa*l, 67(4), pp. 1405-1415.
[9] Wei X.Y, Lu D.J, and Jiang Z.D. 2005 Gaseous slip flow in parallel plates microchannel *J. Micronanoelectronic technology*, (3), pp.129-132.
[10] Ding X.X, Pu J.J, Han M.J, et al. 2011 Calculation and analysis of gas film stiffness in the spiral groove gas seal based on the second order slip boundary *J. Journal of mechanical engineering*, 47(23), pp.119-124.
[11] Muijderman, E.A. 1966 Spiral groove bearings, *BATHGATE R H trans* (New York: Springer-Verlag), pp.17-21.
[12] Song, P.Y，Zhang, S.，and Xu, H.J. 2016 Analysis of performance of spiral groove dry gas seal considered effects of both real gas and slip flow *J. CIESC Journal*, 4, pp.1405-1415.