Friction Characteristics of the Spiral Groove Mechanical Seal

Penggao Zhang¹*, Long Wei¹, Xiu Feng¹, Fei Feng¹
¹Nanjing Polytechnic Institute
Nanjing, China
*zhangpenggao@njpi.edu.cn
Corresponding author: 249954371@qq.com

Abstract—Based on Muijderman narrow groove theory, the pressure distribution of lubricant film in a spiral groove mechanical seal was calculated, and the friction characteristics between the end faces were analyzed. It has been found that the rotating speed has a greater influence on friction, and the friction between sealing faces increases with the increase of rotating speed. The friction between the end faces in a spiral groove mechanical seal decreases with the increase of the angle and depth of the spiral grooves.

1. INTRODUCTION

Texturing different hydrodynamic grooves on the end face of sealing ring has been recently a hotspot in improving the performance of mechanical seal. Wang et al. studied the gas-film-lubricated mechanical face seal with two-row herringbone spiral grooves, and found that it has better damping and restricting effects as compared with gas seals with single-row spiral grooves [1]. Bai, et al. experimentally investigated the friction and wear performance of an elliptical dimpled mechanical seal, and found surfaces with double row elliptical dimples have smaller friction coefficient and lower face temperature than that of the single row elliptical dimples[2]. Jiang, et al. compared the performances of a series of bionic groove dry gas seals, and found that cluster spiral groove and multi-array spiral groove dry gas seals had superiority in the film stiffness and stiffness-leakage ratio compared with common spiral groove under the condition of high speed and low pressure [3-4]. Sun et al. presented a pump-out hydrodynamic mechanical seal with self-pumping effect based on centrifugal pump’s working principle, which can be used in condition with larger pressure difference [5]. Chen, et al. put forward a hyperelliptic curve groove dry gas seal, and studied its dynamic characteristics and transient sealing performance [6]. Xue, et al. studied the effects of groove shape optimization on cavitation and lubricating characteristics of microgroove rotary seals [7]. In this work, the pressure distribution of lubricant film in a spiral groove mechanical seal was calculated based on Muijderman narrow groove theory, and the friction characteristics between the end faces were analyzed.

2. FORCE MODEL OF ROTATING RING IN A SPIRAL GROOVE MECHANICAL SEAL

The mechanical seal is mainly composed of a stationary ring and a rotating ring, the water flows through the sealing gap between the stationary ring and rotating ring, as shown in Figure 1. The shallow spiral grooves textured on the end face of the rotating ring (Figure 2) are expected to pump the magnetic fluid to flow through the gap between the rotating and stationary rings, where the film hydrodynamic pressure is generated to separate the two faces and prevent the leakage of sealed medium.
When mechanical seal is under steady state, the opening force $F_0$ generated by lubricant film is equal to the closing force $F_c$, i.e.,

$$F_c = F_0$$  \hspace{1cm} (1)

where $F_c$ is closing force and $F_0$ is opening force.

3. ANALYTICAL CALCULATION APPROACH OF LUBRICANT FILM PRESSURE BETWEEN END FACES

3.1 Governing Equations of Lubricant Film Pressure
The analytical analysis approach carried out in the work is based on the Muijderman narrow groove theory, and the following assumptions are made to simplify the calculation.

1. The sealing face is flat and film thickness is constant.
2. The dynamic viscosity of the lubricant is constant.
3. The effect of the centrifugal inertial force is not taken into account.
4. The lubricant is the laminar flow.

According to the narrow groove theory of Muijderman[8], the governing equations of lubricant film pressure between the end faces along the radial of sealing ring are

In the region of sealing dam,

$$\frac{dP}{dr} = \frac{6\mu \rho}{\pi h_1^2} \frac{1}{r^3}$$  \hspace{1cm} (2)

In the region of spiral groove,
\[
\frac{dp}{dr} = \frac{6 \mu q_m}{h_i^2} r + \frac{6 \mu q_m g_2}{\rho h_i^2} \frac{1}{\rho r} \tag{3}
\]

where \( g_1 \) and \( g_2 \) are the coefficients of spiral grooves respectively, and

\[
g_1 = \frac{\gamma H_i^3 \cot(1 - H_i) H_i \cot(1 + \gamma)}{(1 + \gamma H_i^2) H_i + H_i^3 \cot(1 + \gamma)^2}
\]

\[
g_2 = \frac{(1 + \gamma) H_i \gamma H_i^3 \cot(1 + \gamma)}{(1 + \gamma H_i^2) H_i + H_i^3 \cot(1 + \gamma)^2}
\]

where \( q_m \) is the mass flux of water, \( \text{kg} \cdot \text{s}^{-1} \), \( \rho \) is the density of water, \( \text{kg} \cdot \text{m}^{-3} \), \( h_0 \) is the film thickness of lubricant film, \( m \), \( h_1 \) 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, \( m \), \( \omega \) is the angular velocity of rotation of seal ring, \( \text{rad} \cdot \text{s}^{-1} \), \( \alpha \) is the angle of spiral groove, \( \text{º} \), \( \gamma \) is the ratio of width of groove to weir, \( H_i \) is the ratio of the film thickness in the sealing dam to spiral groove, and \( H_i = h_0/(h_0 + h_g) \).

### 3.2 Solution of governing equations

The boundary conditions of Eqs. (2) and (3) 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.

Integrating equation (2) from \( r_i \) to \( r \), and substituting \( p(r=r_i) = p_i \) into it gives

\[
p_d = p_i + \frac{6 \mu_h q_m}{\rho h_i^2} \ln \frac{r}{r_i} \tag{4}
\]

where \( p_d \) is the pressure in sealing dam.

Substituting \( r=r_g \) into equation (4), and

\[
p_g = p_i + \frac{6 \mu_h q_m}{\rho h_i^2} \ln \frac{r_g}{r_i} \tag{5}
\]

where \( p_g \) is the pressure at root radius of spiral groove.

Thus,

\[
q_m = \frac{\pi h_i^3 (p_g - p_i)}{6 \mu \ln \frac{r_g}{r_i}} \tag{6}
\]

Integrating equation (3) from \( r_g \) to \( r \), equation (7) is obtained.

\[
p_s = p_g - \frac{3 \mu g_1}{h_i^2} \left( r^2 - r_g^2 \right) + \frac{6 \mu g_2 q_m}{\pi h_i^2} \ln \frac{r}{r_g} \tag{7}
\]

where \( p_s \) is the pressure in spiral groove.

Substituting \( p(r=r_0) = p_0 \) into equation (7) gives

\[
p_g = \frac{h_i \ln \frac{r_g}{r_i}}{h_i \ln \frac{r_g}{r_i} + g_2 h_i \ln \frac{r_0}{r_g}} \left[ p_0 + \frac{3 \mu g_1}{h_i^2} \left( r_0^2 - r_g^2 \right) + \frac{g_2 h_i p_1 \ln \frac{r_0}{r_g}}{h_i \ln \frac{r_g}{r_i}} \right] \tag{8}
\]
According to equation (6) and equation (7), \( q_m \) can be determined. Substituting \( q_m \) into equation (4) and equation (7), \( p_d \) and \( p_s \) can be obtained.

4. **Friction Characteristics of Lubricant Film Between End Faces**

The opening force, \( F_0 \), of lubricant film between the end faces is

\[
F_0 = \int_{r_1}^{r_2} 2\pi r d r + \int_{r_1}^{r_2} 2\pi r d r
\]

(9)

The friction force, \( F_m \), between end faces of mechanical seal can be written as

\[
F_m = \int_{r_1}^{r_2} \frac{2\mu \omega \rho_1^2}{h_i} d r + \int_{r_1}^{r_2} \frac{2\mu \omega \rho_1^2}{(1+\gamma) h_i} d r - \int_{r_1}^{r_2} \frac{2\mu q_{m1} g_{10}}{\rho h_i} d r
\]

(10)

where

\[
g_3 = \gamma + H_1 + \frac{3\gamma H_1 (1 - H_1^2) (1 + H_1^3)}{(1 + \gamma H_1^3)^2} + H_1^3 \cot^2 \alpha (1 + \gamma) \]

\[
g_{10} = \frac{3\gamma H_1 \cot \alpha (1 - H_1) (1 - H_1^2)}{(1 + \gamma H_1^3)^2} + H_1^3 \cot^2 \alpha (1 + \gamma)
\]

The friction coefficient \( f \) between end faces can be written as

\[
f = \frac{F_m}{F_0}
\]

(11)

5. **Results Analysis and Discussion**

The sealed medium is 20 °C water. The parameters of spiral groove mechanical seal are listed in Table I, and the main geometrical parameters of the spiral groove are listed in Table II.

### Table I. Parameters of Spiral Groove Mechanical Seal

| Parameters                  | Value | Unit |
|-----------------------------|-------|------|
| Medium pressure, \( p_0 \) | 0.201 | MPa  |
| Ambient pressure, \( p_i \) | 0.101 | MPa  |
| Rotating speed, \( \omega \) | 200   | rad/s|
| Closing force of mechanical seal, \( F_c \) | 1.5   | kN   |

### Table II. Main Geometrical Parameters of the Spiral Groove

| Parameters                           | Value | Unit |
|--------------------------------------|-------|------|
| Inner radius, \( r_j \)              | 52    | mm   |
| Root radius of spiral groove, \( r_g \) | 39.4  | mm   |
| Outer radius, \( r_i \)              | 34    | mm   |
| Depth of grooves, \( h_g \)          | 10    | \( \mu \)m |
| Spiral groove angle, \( \beta \)     | 15    | °     |
| Ratio of width of weir to grove, \( \gamma \) | 1     | |
| Ratio of groove length, \( l \)      | 0.7   |      |
| Number of spiral groove              | 12    |      |
5.1 Effects of the $F_c$ and $\omega$ on the friction characteristics

The effects of $F_c$ and $\omega$ on $h_i$, $F_m$ and $f$ are illustrated in Figure 3. The film thickness $h_i$ decreases with $F_c$, but increases with the increase of $\omega$. The friction force $F_m$ increases with $F_c$ and $\omega$. The friction coefficient $f$ increases with $\omega$, however, decreases with $F_c$ slightly.

The rotating speed has a significant influence on friction in a spiral groove mechanical seal. Both $F_m$ and $f$ increase with the increase of $\omega$. The closing force $F_c$ increases, and the film thickness $h_i$ decreases, so the friction force $F_m$ increases. However, the increase of $F_m$ and the decrease of $f$ are less than 3 N and 0.001 respectively, when $F_c$ increases from 1 kN to 2 kN under a certain $\omega$, so the effect of $f$ on friction is slightly.

Figure 3. Effects of $F_c$ and $\omega$ on friction characteristics
5.2 Effects of the $\gamma$ and $\alpha$ on the friction characteristics

The effects of $\gamma$ and $\alpha$ on $h_i$, $F_m$ and $f$ can be seen in Figure 4. The $h_i$ increases at first and then decreases with $\gamma$, and increases with the increase of $\alpha$. $F_m$ and $f$ increase with $\gamma$, but decreases with $\alpha$. With the increase of $\gamma$, the pumping effect of the spiral grooves increases, and mass of the sealed medium in the sealing gap increases, thus the friction between end faces increases. Because $h_i$ increases with $\alpha$, the gap between end faces increases, so the friction decreases.

Figure 4. Effects of $\gamma$ and $\alpha$ on friction characteristics
5.3 Effects of the $h_g$ and $m$ on the friction characteristics

The effects of $h_g$ and the width of sealing face, $m$, on $h_i$, $F_m$, and $f$ are showed in Figure 5. The $h_i$ increases with $h_g$ and $m$, and the $F_m$ and $f$ increase with $m$, but decreases with $h_g$. With the increase of $h_g$, the mass of the sealed medium in the sealing gap increases, and the opening force of lubricant film increases, which makes the clearance between end faces increase, therefore the friction between end faces decreases. The increase of $m$ makes the friction area increase, and the $F_m$ and $f$ increase.

Figure 5. Effects of the $h_g$ and $m$ on friction characteristics
6. CONCLUSIONS

1) Based on Muijderman narrow groove theory, the pressure distribution of lubricant film was calculated, and the parameters of friction characteristic between the end faces were analyzed.

2) The rotating speed has a significant influence on friction in a spiral groove mechanical seal, and the friction between sealing faces increases with the increase of rotating speed.

3) The friction between the end faces decreases with the increase of the angle and depth of the spiral grooves.

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