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A Simulation Analysis and Experimental Research on T Groove End Face Seal under Mid-and-Low Speed

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Whether the dry gas seal in the low speed and large diameter of axle equipment can establish a stable gas film is essential to the stability of equipment operation. This is an inevitable requirement to maintain non-contact operation of dry gas seal in service. Choosing T Grooved dry gas seal which can realize bi-direction rotating and on the basis of optimized trough by Fluent software for simulation analysis. Obtain the influence rule of geometric parameters and operating parameters on the properties of T shaped groove dry gas seal under the low speed (<6000 r/min). At the same time, the law is verified through the experiment. The results show that the operating parameters, such as speed and pressure have obvious effects on the properties of sealing. Geometric parameters, like the groove depth and groove number have obvious effects on the sealing performance. Finally, the general principles in choosing working parameters and geometric parameters of T Grooved dry gas seal under low-speed were abtained: Groove number should be between 12~16, groove depth should be between 4~6 μm, sealing clearance between 2~4 μm. The research is instructive to provide theoretical support for engineering design and industrial application of T Grooved dry gas seal under mid-and low speed.

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1. Introduction

With decades of development, the application of dry gas seal in high speed equipment have been increasingly mature. In view of the smaller leakage, lower abrasion loss, longer service life and other excellent features, many occasions of mid-and-low speed began to use dry gas seal instead of traditional contact mechanical seal.[1-3] In the conditions of mid-and-low speed, it is not easy for sealing pair to set up a relatively stable gas film which can isolate dynamic ring from static ring which easy to cause early failure.[4,5] So, the research of sealing performance on this working condition has a theoretical guide role of reducing early failure rate. In recent years, the research on the performance of dry gas seal under med-and-low speed is relatively few. In 2003, Xu Wan-fu[6] carried on theoretical analysis and experimental research on spiral groove dry gas seal under low speed (4000 r/min), the test data showed that this kind of groove type has a good stability. In 2006, Li Wei[7] studied the influence of the roughness of the dry gas seal on the sealing performance under the low speed operation, the results showed that when the ratio of the root mean square value of the film thickness and roughness was greater than 3~4, the influence of the surface roughness on the sealing performance can be negligible. In 2010, Hao Mu-ming[8] studied the steady state response of dry gas seal at low speed of numerical analysis, concluding that without changing other operating conditions, reducing the film thickness or initial angle deviation can make the seal ring with smaller disturbances in the operation process. In 2014, Peng Xudong[9] improved the groove type in the spiral groove dry gas seal under low speeds by drawing from bionics, showing the bionic groove type has higher stability and better sealing.

The groove's asymmetrical structure, making the unidirection rotary dry gas seal can only work in the forward, and reverse rotation caused by human factors will directly leads to seal failure.[10-12] Symmetrical groove dry gas seal in the bi-direction rotating also has a good dynamic pressure effect, which can replace unidirectional dry gas seals under many conditions. Therefore, people pay more attention to the research of dry gas seal with bidirectional rotation performance.[13] The results which studied by the author showing that the changes in geometric parameters of T Grooved has a greater influence on sealing performance. This paper select the symmetrical T Grooved dry gas seal as the research object, on the basis of groove type optimization,[14] through simulation analysis and experimental verification, the influence of the sealing performance parameters of the T type groove in the middle-and-low speed is obtained.

2. Theoretical Model

2.1 Hypothetical condition

Based on the theory of fluid mechanics, as well as considering the structure of the sealing ring and sealing system, the following assumptions were made to analyze the steady flow field in gas film between the seal faces:[15]

(1) The flow of the gas among the seals is continuous medium flow;

(2) The gas in the gas film is the Newtonian fluid for laminar flow movement;[16]

(3) In the condition of non-contact state, ignoring the change of the temperature, and assuming that flow field temperature, viscosity is equal everywhere;

(4) Assuming the gas pressure and density in the direction of film thickness are constant because the film is very thin;

(5) There is no relative slip between gas molecules and sealing surface;

(6) Ignoring the effects caused by the sealing ring deformation on gas flow;

(7) Ignoring the effects of the end surface roughness of sealing on gas flow;[17]

(8) Ignoring the disturbance and vibration in the working process of the system's influence on the flow field of gas film.

2.2 Mathematical model

Based on the above assumptions, the expression of the dimensionless Reynolds equation under cylindrical coordinate system is:[8,9]

$$\frac{\partial}{R\partial R}\left(PH^3R\frac{\partial P}{\partial R}\right)+\frac{\partial}{R\partial\theta}\left(PH^3\frac{\partial P}{R\partial\theta}\right)=\frac{6\mu\omega(r_0/h_0)^2}{P_0}\frac{\partial(PH)}{\partial\theta} \tag{1}$$

The dimensionless parameters in formula (1) are defined as: $R = r/r_o$, $P = p/p_o$, $H = h/h_o$, where r_o is outside radius; p_0 is outside pressure; h_o is the film thickness in addition to the groove area external.

In order to achieve precise calculation and the experimental results, this article chooses OTG[18] (Optimized T-Groove) for research. Given that the axial symmetry geometry structure of T Grooved in annular groove seal face. As shown in Fig. 1(a), the regional flow field theoretically is the same. Therefore, take out one arbitrary area to calculate is enough.[11] Fig. 1(b) is sampling area by haphazard selection.

Boundary conditions are shown as follows:

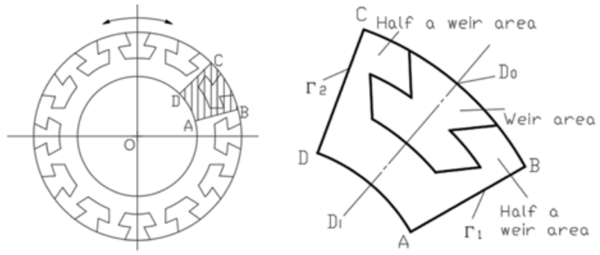
(1) Mandatory boundary conditions Ω_1:

At the place of r_i, P_{in} means pressure, which is atmospheric pressure;

At the place of r_o, P_{out} means pressure, which is outside-changing pressure.

(2) Periodic boundary condition Ω_2:

The pressure in the symmetrical boundary Γ_1 and Γ_2 is equal. That is: $p(\theta+2\pi/N_g) = p(\theta)$. According to the conservation of mass flow rate, the mass flow rate passed boundary Γ_1 and Γ_2 is respectively equal: $q|\Gamma_1 = q|\Gamma_2$. We can calculate the seal performance parameters like open end force, leakage rate and gas film stiffness after calculating the pressure distribution at seal face through the simulation. The calculation method can be found in Ref. 19.



(a) Grooved end face (b) Sampling calculation area

Fig. 1 Geometric model of OTG dry gas seal

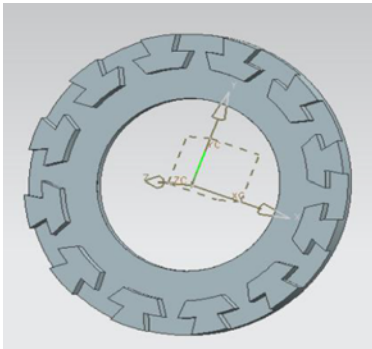


Fig. 2 Computational domain

3. Simulation Analysis of Dry Gas Seal

3.1 Simulation modeling

Fig. 2 is using the UG software to draw the entire T Grooved seal gas film flow field. There are many software to choose to establish the three-dimensional flow field, such as UG, Pro/E, Solidworks and others, The established process was similar, when imported to the Gambit for meshing, 3D entity established by UG can be automated divided into two adjacent separate entity, it is more convenient to mesh generation. In view of the radial size and film thickness ratio to 4 orders of magnitude, Figs. 2 and 3 film thickness direction size is 1000 times of magnification.

3.2 Mesh generation and solution set

When using Gambit software for meshing, due to the size of the gas film thickness direction and transverse radial size difference to 4 orders of magnitude. Meticulous division for the radial dimensions can lead to huge grid number, and that could affect the simulation time and computing speed seriously. Related literature 15 shows that when the number of grid is greater than 200 × 200, the sealing performance remains unchanged, and the calculation error is less than 1%. So in the actual meshing generation, choose line-plane-body order and Cooper method to generate axial structured grid, it can meet the accuracy requirement.

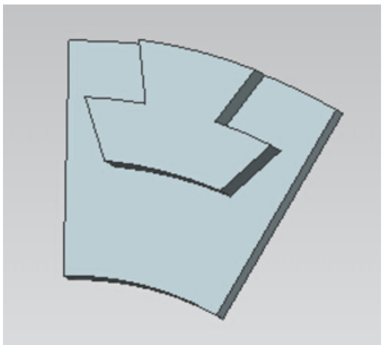


Fig. 3 Three-dimensional analysis model of gas film

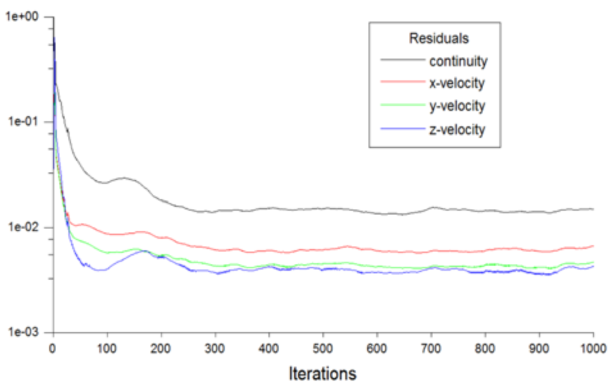


Fig. 4 Convergence curve

Table 1 Simulation parameters

Geometric parameters		Operating parameters	
Inside diameter r_i	51 mm	Internal pressure P_{in}	0.1013 (MPa)
Outside diameter r_o	89 mm	External pressure P_{out}	0.1-0.5 (MPa)
Root diameter r_g	69 mm	Viscosity	$1.8\times10^{-5}\mu$ (Pa·s)
Mid-diameter r_m	79 mm	Rotate speed	0-6000 (r/min)
Groove number N_g	6-20		
Groove number h_g	1-6 μm		

Select the three-dimensional single precision solver as fluent simulation solver. The model is set to a non viscous (ideal) fluid, and the pressure-speed coupled with SIMPLEC algorithm. Discrete format of diffusion term adopts the central difference scheme, and the discrete format of convection item adopts second-order windward format in order to improve the accuracy of the calculation results. The iterative precision of the model is set to be 10^{-3}.

3.3 The simulation parameters

Geometric and operating parameters of OTG dry gas seal were shown in Table 1 which contains diameters, groove numbers, pressure, viscosity and rotating speed.

3.4 Simulation results

The effect of groove number N_g on the opening force and leakage is shown in Fig. 5(a). It shows that firstly the gas leakage rate and the opening force increases with the increase of the number of grooves, and then tends to be stable. When the groove number is less than 12, the gas film stiffness increases rapidly, and when the groove number is more than 14, it showed a slow downward trend. With more grooves, it's more difficult to manufacture. Therefore, to take into account the cost of production and stiffness characteristics, the number should be between 10 to16. The Fig. 5(b) shows that the increase of groove depth causes the increase of the leakage rate, and the decrease of the opening force. Overall, groove depth should between 4 to 6 μm. In the same way, the analysis of Fig. 5(c) shows that the effect of film thickness on opening force and leakage rate. Ideal sealing film thickness is between 2 to 4 μm, this interval can realize the higher opening force, also won't cause great leakage.

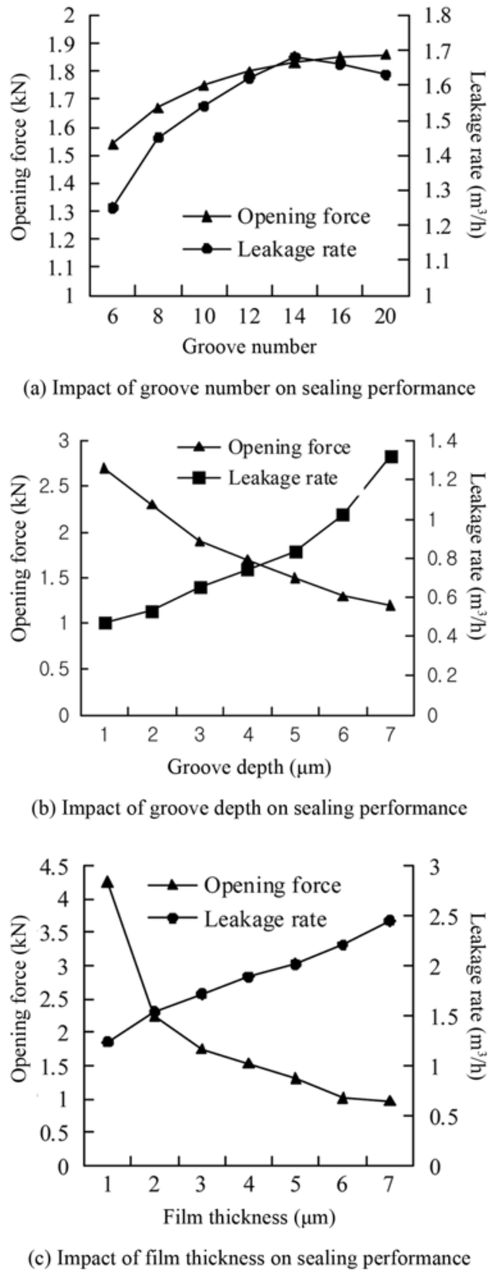


Fig. 5 The parameters affecting the sealing performance of groove

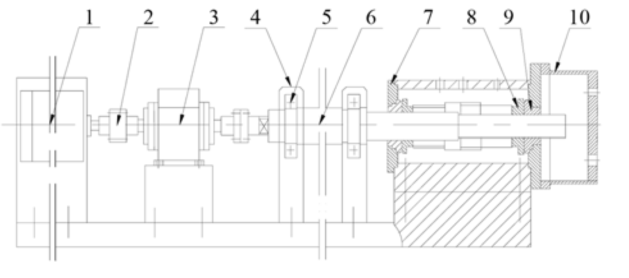


Fig. 6 Sealing experiment device: 1.Grinding head motor, 2. Coupling, 3. Speed and Torque sensor, 4. Bearing seat, 5. Bearing, 6. Principal axis, 7. Sealed cavity, 8. Sealing ring, 9. Seal static ring, 10. Leaky cavity

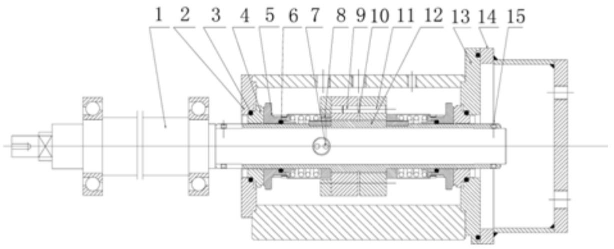


Fig. 7 Seal chamber: 1. Principal axis, 2. Left end cover, 3. Sealing ring, 4. Static ring, 5. Moving ring, 6. Sealing ring, 7. Adjusting hole, 8. Spring seat, 9. Left push ring, 10. Guide pillar, 11. Right push ring, 12. Axle sleeve, 13. Right end cover, 14. Leakage end cover, 15. Set screw

4. Dry Gas Seal Test Device

Fig. 6 is the experimental apparatus during the PhD period for the study of dry gas seal, on the basis of the original contact type mechanical seal test to redesign seal cavity. As shown in Fig. 7, Seal chamber improvement work includes: Design appropriate penetrating sleeve, solve the problem of sealing pair is not good for centering and can not accurately set the pressure. According to the shaft sleeve position to process the shaft. According to the size of the shaft sleeve to design the pushing ring. Designing the fixed device of the left push ring and the moving ring seat.

Experimental device technical indicators are as follows: Range of speed is 0~6000 r/min. Pressure of sealing is 0~0.5 MPa., The shaft neck is 50 mm. The measurement range of leakage is 0.2~2 m^3/h. The measurement range of torque is 0~20 Nm. The measurement range of temperature is 0~100^{o}C. Sealing parameter selection is the same as simulation, as shown in Table 1. The material of rotating seal ring is cemented carbide YG8, the material of static ring is carbon graphite. The sealing medium is pressure drying air. Instrument used for slotting is LM-50B type semiconductor marking machine. The groove is shown in Fig. 8. The roughness is removed by circular processing under the low power and the burr is removed by grinding machine.

In this experiment, torque value includes the end face friction torque as well as the bearing friction torque, which has no effect on sealing performance trend researching. It needs corresponding research if we want to know the accurate friction torque.

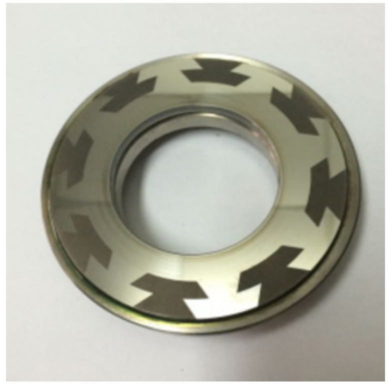


Fig. 8 OTG groove of the experiment

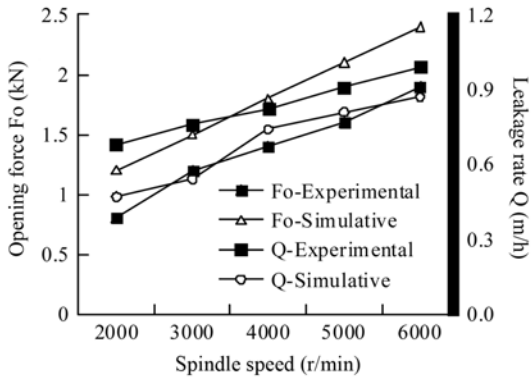


Fig. 9 Influence of rotating speed on opening force and leakage

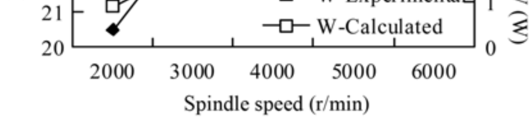


Fig. 10 Influence of rotating speed on the gas film stiffness and the friction power consumption

5. Comparison and Discussion of Results

5.1 The influence of operating parameters on sealing performance

5.1.1 Spindle speed

The effect of spindle speed on the performance of OTG dry gas seal is shown in Figs. 9 and 10. The figure shows that opening force and leakage increase linearly with the speed. The main reason is that accompanied by spindle speed increases, the gas entered the OTG

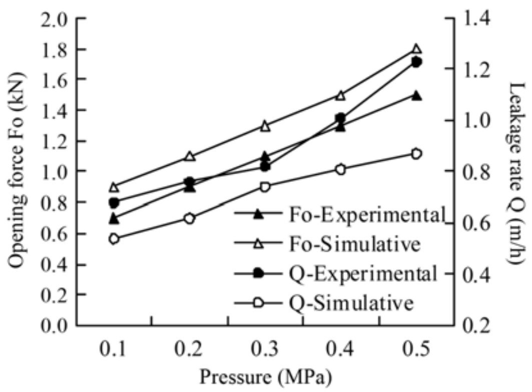


Fig. 11 Influence of pressure on the opening force and leakage

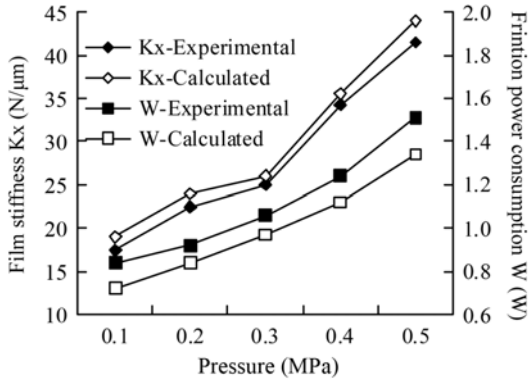


Fig. 12 Influence of pressure on the gas film stiffness and the friction power consumption

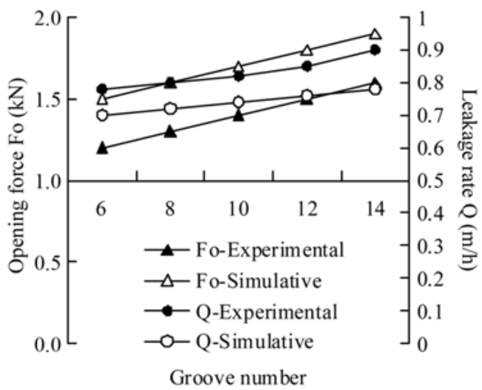


Fig. 13 Influence of groove number on opening force and leakage

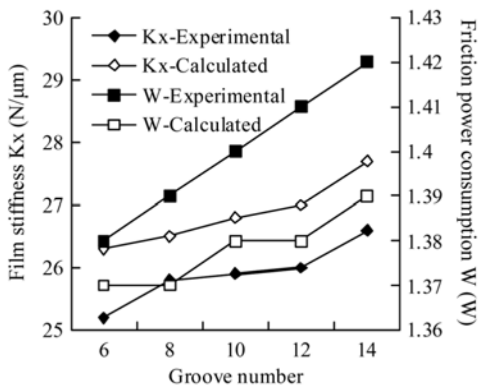


Fig. 14 Influence of groove number on the gas film stiffness and the friction power consumption

increases, a larger high pressure region is formed in T-groove, causing an opening force increases; At the same time, the leakage gas from the T-groove to the inner diameter increased, and the leakage quantity is enlarged. The gas film stiffness and friction power consumption increase linearly with the increase of the rotational speed, this dues to the fact that gas film stiffness is proportional to opening force. With the increase of rotational speed, the shear force of the seal is also increased. As a result, the friction force increases, then the friction power consumption increases too.

5.1.2 Pressure

The influences of pressure on the sealing performance is shown in Figs. 11 and 12. It can be seen from the figure that opening force and leakage increased linearly with the increase of pressure. This is due to the increase of the gas pressure in the OTG, which promotes the increase of the airflow pressure in the T Grooved, thus increasing the opening force, at the same time, the leakage of gas in the unit time also increased. With the increase of pressure, the gas film stiffness and friction power consumption also increased.

5.2 The influence of geometric parameters on seal performance

5.2.1 Groove number

Figs. 13 and 14 shows that Grooved number increases with the opening force in positive correlation. This is because each groove can form a certain opening force and cause the corresponding leakage. According to the simulation results, According to the simulation results, the influence of a certain number of grooves on the opening force is not obvious. And increasing the number of grooves will not only increase the amount of leakage, but also increase the difficulty of processing, so the number of grooves should not be too much. This can be used to explain the change trend of the gas film stiffness. Friction power consumption also increased due to the accumulation of the number of grooves.

5.2.2 Groove depth

Figs. 15 and 16 shows that there is a negative correlation between groove depth and opening force, which is due to the increase of the groove depth, the gas film static pressure decreases, and the gas film stiffness has become smaller. The leakage of unit volume increase significantly with the increase of the sealing clearance. With the increase of the groove depth, the change of the friction power consumption decreases obviously. According to the experimental parameters, when the groove depth increases to 4 μm, the influence of the friction power consumption is basically unchanged.

5.3 Analysis of experimental error

Through the comprehensive analysis of the experimental results and Fluent simulation values, it can deduce that leakage, opening force, gas

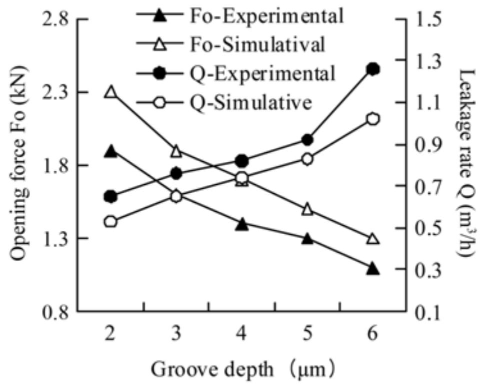


Fig. 15 Groove depth influence on opening force and leakage

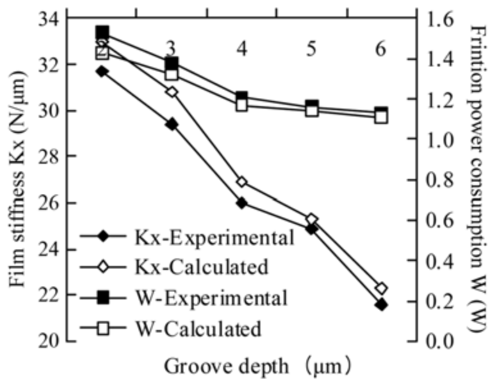


Fig. 16 Influence of groove depth on the gas film stiffness and the friction power consumption

film stiffness and friction power change are basically consistent with the change of structure parameters of the OTG dry gas seal. Judging from the data, experimental and simulated values exist certain errors. Fluent simulation values are obtained through the Fluent software simulation, and the experimental values are achieved by dry gas seal test. There are many unstable factors in the experiment, the causes of the error may be as following:

Simulation calculations set the gas film thickness as a constant, but in the actual experiment, the gas film thickness is changing.

In the simulation experiment, the model of the gas film is smooth, but under the condition of the existing laser grooving equipment in the laboratory, there is a certain degree of roughness at the bottom of the groove.

When the simulation experiment is carried out, the dry gas seal experiment device is not involved. And in the experiment, it is difficult to maintain the seal faces completely parallel to the joint.

In simulation experiments, we do not consider the temperature of the seal chamber and the thermal deformation of the seal face. However, in the actual experiment, the increase of seal chamber temperature leads to thermal deformation of seal face. Sometimes it will lead to seal faces off and the leakage increase.

Therefore, it is not easy to complete the OTG dry gas seal test under the condition of the laboratory. Although the error of experiment value and simulation value is relatively large, the change rules of the OTG dry gas seal performance parameters are basically consistent with the simulation. So seal experiment is still very meaningful.

6. Conclusion

(1) Opening performance at low speeds is the main technical index of dry gas seals successfully applied to the low speed shaft diameter and large shaft diameter equipment. Groove type optimization and the choice of groove geometry parameters that under certain conditions are very important.

(2) The effect of rotating speed and pressure on the sealing performance is the most significant in the specific working conditions. Especially in the low speed and high pressure conditions, the opening of dry gas seal is more difficult. Under this condition, we can choose contact type mechanical seal. In geometric parameters, the influence of groove depth and groove number on sealing performance is great.

(3) General principles for the selection of working parameters and geometric parameters of T type groove dry gas seal are abtained: Groove number should be between 10 to 16. Depth of the groove should be between 4 and 6 μm. Film thickness ideal range of 2 to 4 μm.

(4) The experimental results are in good accordance with the simulation results. The main reasons for the error lies in the various idealized assumptions and the accuracy of the test system. The overall results can accurately reflect the OTG dry gas seal performance at low speed.

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