TELKOMNIKA, Vol. 11, No. 2, February 2013, pp. 896~905
ISSN: 2302-4046

Influencing Factors of Thermal Deformation on Hydrostatic Pressure Mechanical Seal and Optimization of Rotating and Stationary Rings

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Abstract

According to thermo-elastic deformation theory, take the temperature field analysis results of hydrostatic pressure mechanical seal as volume load to resolve the problem of thermal-structure coupling deformation of rotating and stationary rings in ANSYS software. The distribution laws of thermal strain, thermal stress and thermal-structure coupling deformation are obtained. The effects of working, material and structural parameters on axial, radial thermal deformation and deformation taper of the end faces are discussed in detail, and the main affecting factors are found out. Measures and structural constraint programs to control the thermal deformation are put forward. Base on the theory of thermal deformation compensation, the rotating and stationary rings are optimized, and the thermal deformation before and after their optimization are solved respectively and analyzed comparatively to verify the feasibility of the optimization program.

Keywords: *Hydrostatic Pressure Mechanical Seal, Thermal-Structural Coupling Deformation, Finite Element Method, Optimization*

1. Introduction

Because the dry gas seal has the advantage of low leak, environmental protection, energy saving and long lifetime, so researchers try to use it in more rotating mechanical dynamic seal. But from theoretical analysis and practice, the stability of dry gas seal lies mainly on the rotating speed of a unit [1]. Dry gas seal needs small clearance non-contacting rotating. When the rotating speed is high enough, the small clearance can be formed. Otherwise, the sealing property will drop, even will not work properly. In general, the rotating speed of principal axis of centrifugal compressor is very high which is about 10000 rpm, so dry gas seal is used successfully in this type of equipment. As for lower rotating speed machines such as reaction kettle, etc. , because of its low rotating speed, it is difficult to form adequate gas film opening force and stiffness, so dry gas seal can not work normally. Yu [2] and Liu [3] make use of the theory of externally pressurized gas lubrication bearing to design a new-style hydrostatic pressure mechanical seal which does not depend on the rotating speed of a unit. Its working principle is, the end face stable gas film and high opening force are formed by externally pressurized gas, and non-contacting running is realized. It is a new-style mechanical seal which has types of externally pressurized and interior pressurized structures. The externally pressurized structure has the advantages of stable seal performance and high reliability, good gas film stiffness, not depending on sealing speed, realizing the heavy equipment to start under complete gas-film lubrication conditions, as shown in Figure 1. Its disadvantages are, static pressure gas providing by external gas source equipment, complex structure, and processing difficulties. Because the hydrostatic pressure mechanical seal has the advantage of environmental protection, energy saving, long lifetime, high efficiency and low maintenance cost, so it is widely used in petroleum, chemical and other industry. One of normal work conditions of hydrostatic pressure mechanical seal is stable gas film stiffness which has many affecting factors, such as, the grooved length and width of stationary ring end face, end face roughness of rotating and stationary ring, sealing medium, end face clearance, property of orifice compensation, and so on. Tadashi Koga [4, 5] has researched the seal performance and its application to extreme condition of externally pressurized gas non-contacting mechanical

Received September 1, 2012; Revised December 31, 2012; Accepted January 14, 2013

seal, and the end face pressure distribution, end face opening force, gas film stiffness and balance of forces are discussed in detail. Zhou [6] has studied the externally hydrostatic pressure mechanical seal with orifice compensation. The effects of gas film thickness, pressure of air supply, numbers and diameter of throttle orifice, on end face opening force and gas film stiffness are discussed in detail. In practical application, the gas agitating heat in the sealed chamber and the dissipated power due to viscous friction in the sealing interface will result in a rise in temperature of rotating and stationary rings. Excessively high temperature and temperature gradient will result in thermal deformation of rotating and stationary rings, point contacting between end faces, leakage increasing, unstable gas film. All these problems seriously affect the performances, running safety and lifetime of seal. By thermal equilibrium analysis, Zhu [7] established the solid stable state heat conduction differential equation in three dimensional cylindrical coordinate, and used the ANSYS software to analyze the temperature field of seal pair in hydrostatic pressure mechanical seal. In this article, the amount of heat generated and thermal deformation of externally hydrostatic pressure mechanical seal will be analyzed. The rotating and stationary ring will be optimized by the theory of thermal deformation compensation. All these will provide theoretical basis for optimal design of hydrostatic pressure mechanical seal and get more stable sealing performance and longer lifetime of seal ring.

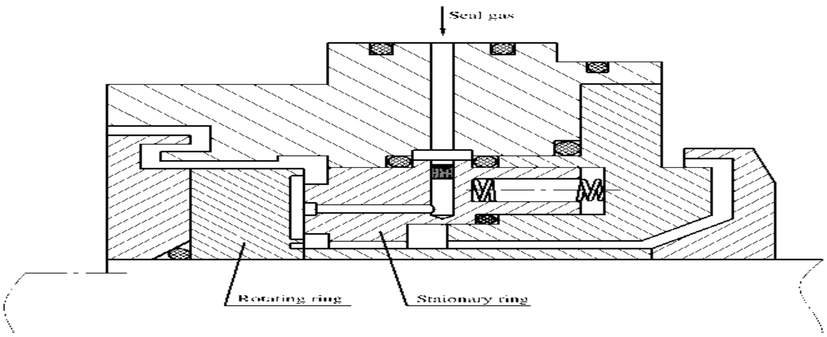

Figure 1. Externally hydrostatic pressure mechanical seal

2. Analysis of Thermal-Structural Coupling Deformation

Non-uniform temperature distribution of seal pair in hydrostatic pressure mechanical seal will result in a certain thermal stress in the structure. That is, thermal stress is closely related to temperature. Thermal strain is closely related to thermal stress and material thermal-expansion coefficient. According to thermo-elastic deformation theory, take the temperature field analysis results of rotating and stationary rings [7, 8] as volume load, and impose on the sealing rings. Add displacement constraints shown in Figure 2 and Figure 3, use separation method and thermal-structure coupling element PLANE42 to resolve the problem of thermal-structure coupling deformation of rotating and stationary rings in ANSYS software. The analyzed results are shown in Figure 4 - Figure 9.

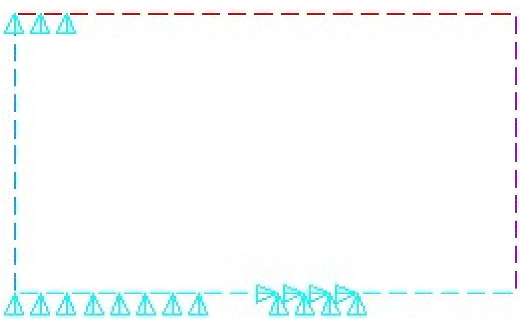

Figure 2. Constraints of Rotating Ring

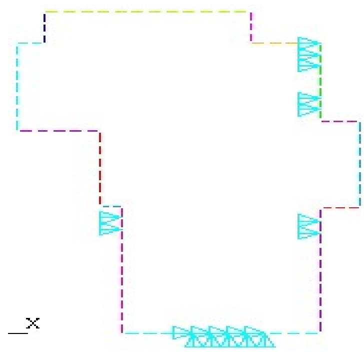

Figure 3. Constraints of Stationary Ring

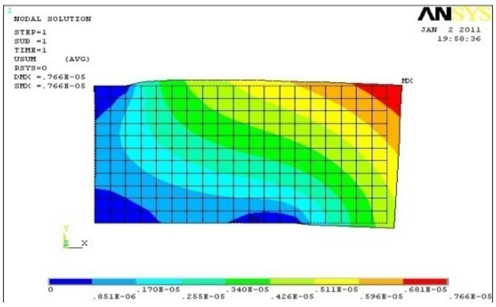

Figure 4. Thermal Deformation of Rotating Ring

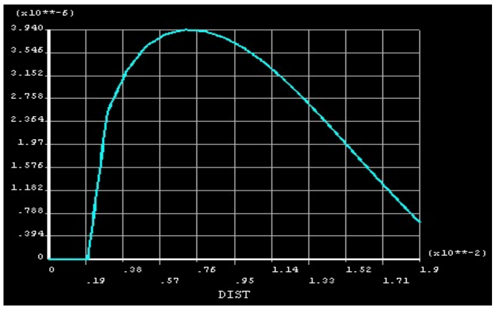

Figure 5. Axial Deformation of Rotating Ring

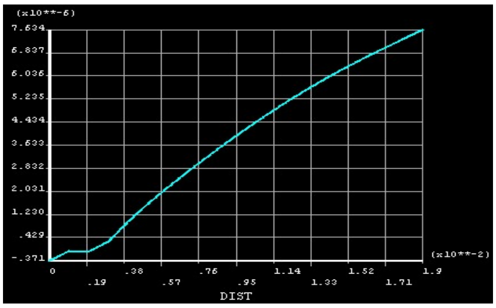

Figure 6. Radial Deformation of Rotating Ring

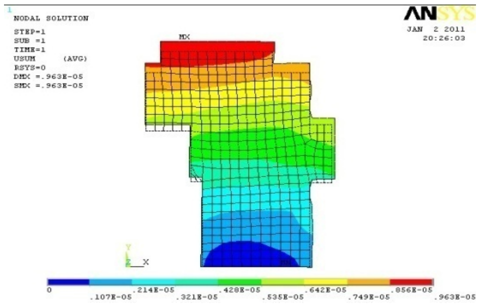

Figure 7. Thermal Deformation of Stationary Ring

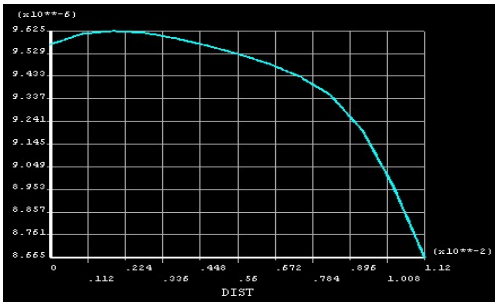

Figure 8. Axial Deformation of Stationary Ring

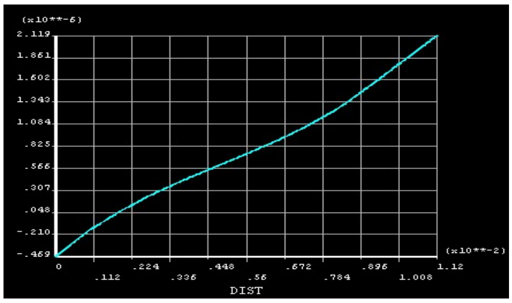

Figure 9. Radial Deformation of Stationary Ring

From Figure 4 and Figure 5, the thermal-structure coupling deformation of the end face of rotating ring is positive conical angle, its maximum axial deformation locating at a place whose distance is 7mm away from the inner diameter is 3.94μm. The maximum deformation of the end face locating at the outer diameter is 7.66μm. The radial deformation of the end face of rotating ring increases linearly from inner diameter to outer diameter, its maximum is 7.63μm, as shown in Figure 6. As for the same node, its radial thermal deformation is greater than its axial thermal deformation, this is caused by thermal boundary conditions and displacement constraints. The temperature distribution law of rotating ring corresponds with the thermal-structure coupling deformation distribution law.

At first, the axial thermal deformation of the end face of stationary ring increases gradually from inner diameter to outer diameter, and then decreases slowly, its maximum axial deformation locating at a place whose distance is 2mm away from the inner diameter is 9.63μm, as shown in Figure 7 and Figure 8. The radial deformation of the end face of stationary ring increases linearly from inner diameter to outer diameter, its changing scope is 2.59μm, as shown in Figure 9. The maximum thermal deformation of the end face of stationary ring locating at a place whose distance is 2mm away from the inner diameter is 9.63μm, so the thermal deformation of the end face of stationary ring depends mainly on the axial thermal deformation. The maximum temperature of stationary ring locates at the outer diameter of end face, the maximum thermal deformation of stationary ring locates at the inner diameter of end face, this is caused by displacement constraints.

3. Main Influencing Factors of Thermal Deformation

The thermal deformation of the seal pair is related to distribution law of temperature field, material characteristic, working parameters and so on. The amount of deformation and the deformation conical angle may describe the thermal deformation. The axial deformation of seal pair has a direct impact on gas film thickness, so it indirectly affects the sealing performance. When the axial deformation increases, the gas film thickness will decrease. When the gas film thickness is very small, the gas film will be unstable, the gas film stiffness will decline sharply, bearing capacity will reduce, even make the end faces contact directly.

3.1. Influencing of Rotating Speed on Thermal Deformation

Assuming other parameters unchanged, analyze the influencing of rotating speed on thermal deformation. Add displacement constraints and thermal boundary conditions of various rotating speed on rotating and stationary rings, the analysis results of thermal deformation are shown in Figure 10-Figure 15.

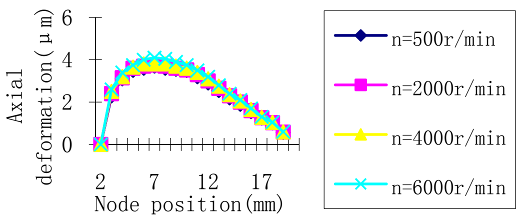

Figure 10. Axial Deformation of Rotating Ring

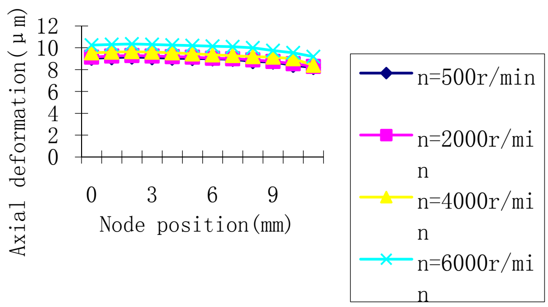

Figure 11. Axial Deformation of Stationary Ring

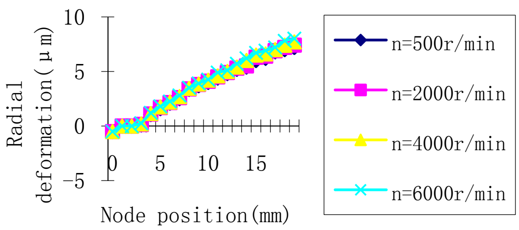

Figure 12. Radial Deformation of Rotating Ring

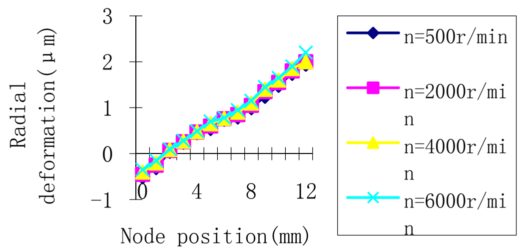

Figure 13. Radial Deformation of Stationary Ring

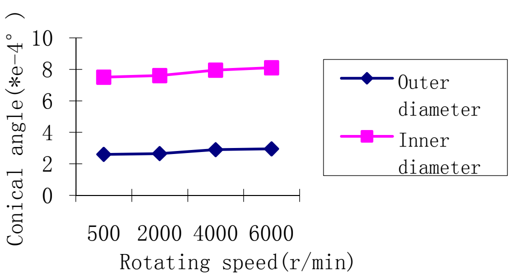

Figure 14. Effect of Rotating Speed on Rotating Ring

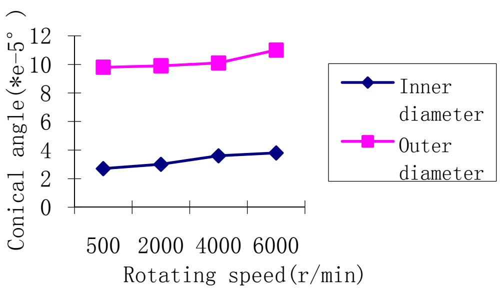

Figure 15. Effect of Rotating Speed on Stationary Ring

The end face axial deformation trend of rotating ring at different rotating speeds is basically the same, as shown in Figure 10. With the increasing of rotating speed, shear heat generated between the end faces increases, end face temperature rise, so the maximum end face axial deformation increases, but the increase is relatively small. The thermal deformation amount at the outer diameter of the end face is increased as the rotating speed increases, but the increase is very small, so it can be neglected. The end face axial deformation trend of stationary ring at different rotating speeds also is basically the same, as shown in Figure 11. The axial deformation amount of each node at the end face increases as the rotating speed increases. When the rotating speed is smaller, the smaller the increasing amount of deformation is. At different rotating speeds, the radial deformation of the end faces of rotating and stationary rings increases linearly from inner diameter to outer diameter, and the deformation increases as the rotating speed increases, but the increase is relatively small, as shown in Figure 12 and Figure 13. At different rotating speeds, the conical angle curves of the end faces of rotating and stationary rings are relatively flat, that is, the conical angle changes of the end faces are small, as shown in Figure 14 and Figure 15. The conical angle of the end faces increase as the rotating speed increases. As for the rotating ring, the conical angle of end face outer diameter is smaller than that of the inner diameter. As for the stationary ring, the conical angle of end face outer diameter is larger than that of the inner diameter.

3.2. Influencing of Thermal Conductivity Coefficient on Thermal Deformation

From Figure 16 and Figure 18, when the thermal conductivity increases, the thermal deformation quantity and conical angle of the end face of the rotating ring remain almost unchanged, the influence of thermal conductivity on thermal deformation can be negated, and the axial deformation is less than the radial deformation, the conical angle of outer diameter is smaller than the conical angle of inner diameter. From Figure 17 and Figure 19, when the thermal conductivity increases, the thermal deformation quantity and conical angle of the end face of the stationary ring remain almost unchanged, the influence of thermal conductivity on thermal deformation can be negated, and the axial deformation is larger than the radial deformation, the conical angle of outer diameter is larger than the conical angle of inner diameter.

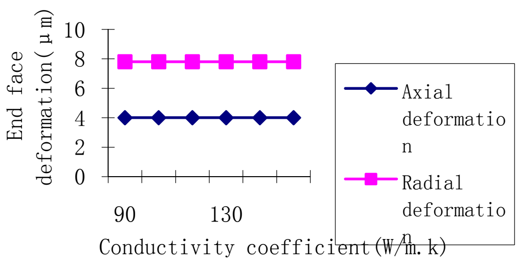

Figure 16. Effect of Conductivity Coefficient on Rotating Ring

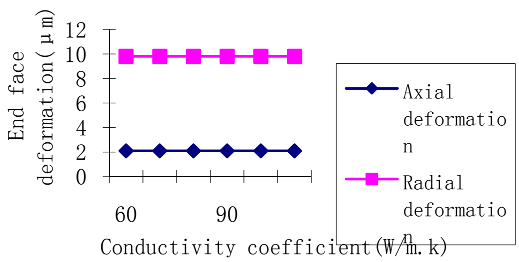

Figure 17. Effect of Conductivity Coefficient on Stationary Ring

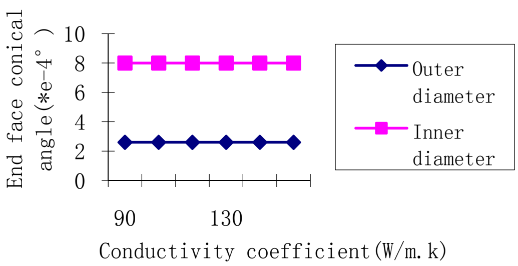

Figure 18. Effect of Conductivity Coefficient on Rotating Ring

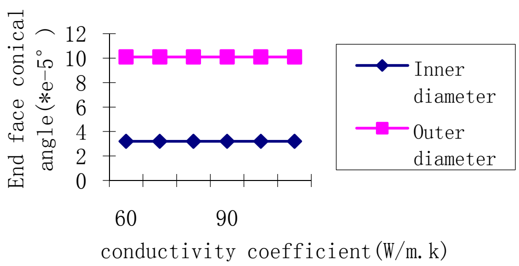

Figure 19. Effect of Conductivity Coefficient on Stationary Ring

3.3. Influencing of Thermal-Expansion Coefficient on Thermal Deformation

From Figure 20 and Figure 22, when the thermal expansion coefficient increases, the thermal deformation quantity and conical angle of the end face of the rotating ring increases, and the axial deformation is less than the radial deformation. The conical angle of outer diameter is smaller than the conical angle of inside diameter, and the conical angle variation of outer diameter is less than that of the inner diameter. From Figure 21 and Figure 23, when the thermal expansion coefficient increases, the thermal deformation quantity and conical angle of the end face of the stationary ring increases, the axial deformation is larger than the radial deformation, and the axial variation significantly is greater than the radial variation. The conical angle of outer diameter is larger than the conical angle of inner diameter, and the conical angle variation of outer diameter is larger than that of the inner diameter.

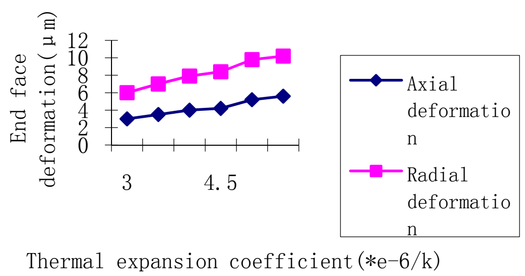

Figure 20. Effect of Thermal Expansion Coefficient on Rotating Ring

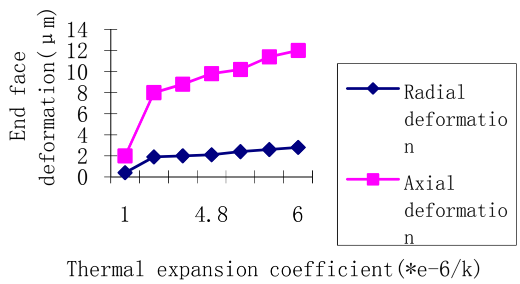

Figure 21. Effect of Thermal Expansion Coefficient on Stationary Ring

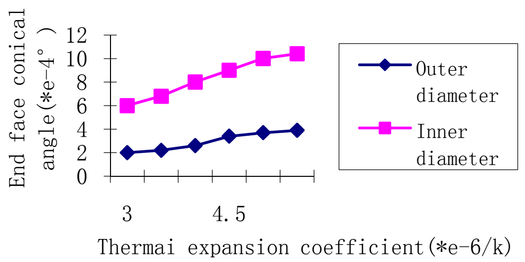

Figure 22. Effect of Thermal Expansion Coefficient on Rotating Ring

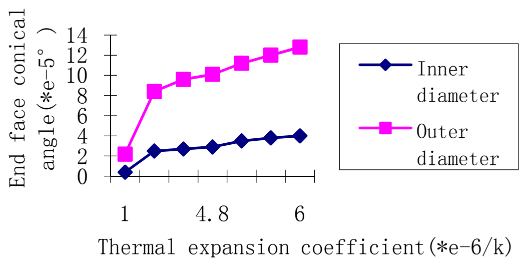

Figure 23. Effect of Thermal Expansion Coefficient on Stationary Ring

3.4. Influencing of Poisson Ratio on Thermal Deformation

From Figure 24 and Figure 25, end face thermal deformation amounts of rotating and stationary rings are increased with the increase of the Poisson ratio. As for rotating ring, the thermal deformation changes slowly, the change is relatively small, and the axial thermal deformation amount is less than the radial thermal deformation. As for stationary ring, the thermal deformation changes quickly, the change is relatively large, and the axial thermal deformation amount is larger than the radial thermal deformation. From Figure 26 and Figure 27, conical angles of end face thermal deformation of rotating and stationary rings are increased with the increase of the Poisson ratio, and the conical angle variations are relatively small. As for rotating ring, the conical angle of outer diameter is smaller than the conical angle of inner diameter, and the conical angle variation of outside diameter is smaller than the conical angle variation of inner diameter. As for stationary ring, the conical angle of outer diameter is larger than the conical angle of inner diameter, and the conical angle variation of outside diameter is almost equal to the conical angle variation of inner diameter.

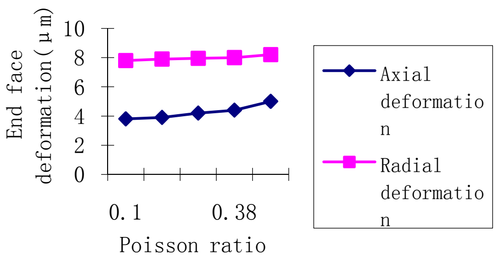

Figure 24. Effect of Poisson Ratio on Rotating Ring

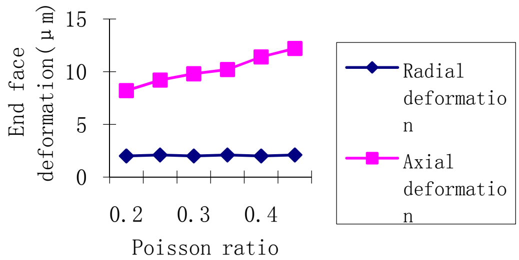

Figure 25. Effect of Poisson Ratio on Stationary Ring

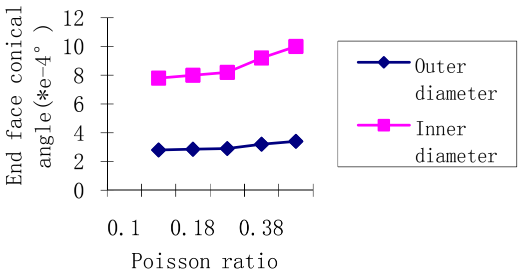

Figure 26. Effect of Poisson Ratio on Rotating Ring

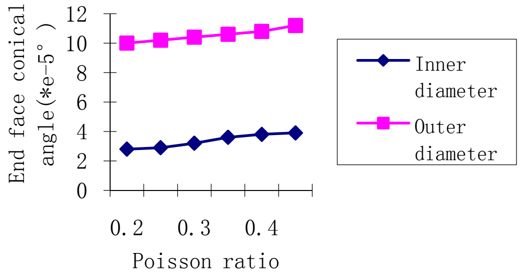

Figure 27. Effect of Poisson Ratio on Stationary Ring

4. Optimization of Rotating and Stationary Rings

4.1. Optimization Methods of Seal Pair

The deformation of the seal pair is a result of both thermal and mechanical loads, that is the coupling of thermal deformation and force deformation, but it is not the simple sum. Therefore, the optimization design of sealing rings should be considered both from reducing thermal deformation and force deformation. By theoretical analysis, reducing thermal deformation can get parallel end face. One of the most effective method is reducing thermal loads and temperature of the end face to get small thermal deformation. So the gas shear heating and stirring hot should be reduced, which can be got by adjusting structure parameters of sealing rings.

End face thermal deformation of the seal rings is closely related to its temperature gradient, so, reducing the temperature gradient can reduce the thermal deformation. Insulating the seal rings and limiting the temperature gradient in the end face of the seal ring can cause the overall temperature distribution of the seal ring to be even. In this condition, the seal ring should have a sufficiently large strength to bear the end face thermal stress. But this method has a disadvantage of reducing the radiating boundary of the seal rings, so the end face temperature is relatively high. Secondly, using high thermal conductivity material can reduce the temperature gradient. From the preceding analysis, reducing thermal expansion coefficient can reduce thermal deformation of sealing ring. In the design of the sealing rings, it should be possible to choose high thermal conductivity, a small thermal expansion coefficient of the composite material. In actual work, the thermal deformation of seal rings cannot be completely eliminated. But we can control the thermal deformation, so that the end face deformation of rotating and stationary rings maintains consistent. That is, after the thermal deformation, the end faces of the seal rings must maintain parallel. This is the theory of optimal design based on thermal deformation compensation [9, 10].

4.2. End FaceThermal Deformation Model of Seal Pair

Only considering the thermal deformation, the end faces of rotating and stationary rings have eight kinds of deformation forms, as shown in Figure 28. In such deformation forms, there are two kinds of parallel deformation, three kinds of convergent deformation and three kinds of divergence deformation. In which, parallel deformation is the ideal thermal deformation control model, convergent deformation is better than divergence deformation. In actual work, there is the possibility that the eight kinds of deformation forms appear, but the divergence deformation must be avoided. By optimal design method, parallel deformation could be obtained. When optimizing the design of rotating and stationary rings, the coordination deformation form not the thermal deformation amount is the core problem.

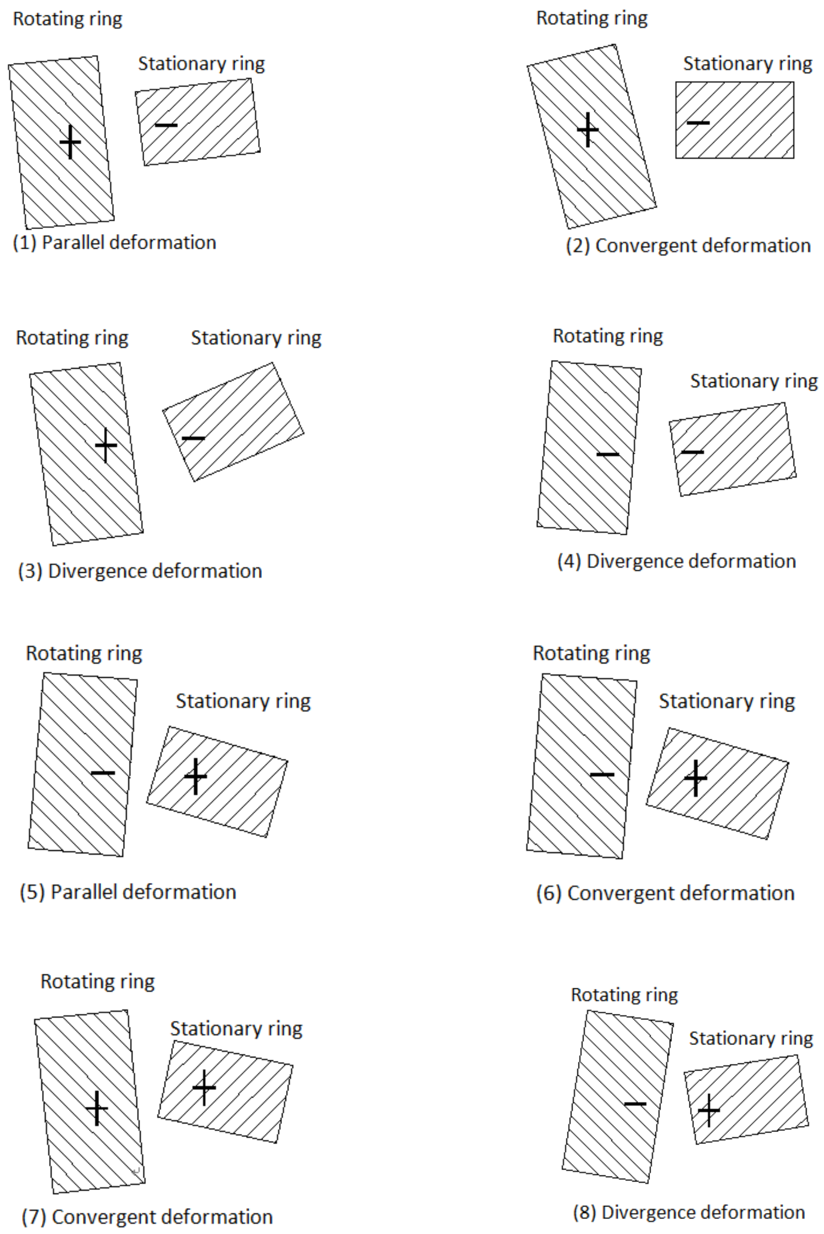

Figure 28. Thermal Deformation Control Models of Seal Pairs

4.3 Optimization of Rotating Ring

Basic assumptions: 1) The material is linear. 2) Neglect the effects of force deformation. 3) Neglect the effects of deformation of adjacent equipments. By adjusting the constraints of the rotating ring or the stationary ring, we can reduce the thermal deformation conical angle of end face, then can optimize the end face deformation form. The main goal of optimization is reducing the convergent conical angle of the end faces to make the end faces tend to parallel.

After several simulation and analysis, the optimized constraints of the rotating ring is shown in Figure 29, the thermal deformation of the rotating ring is shown in Figure 30 – Figure 32.

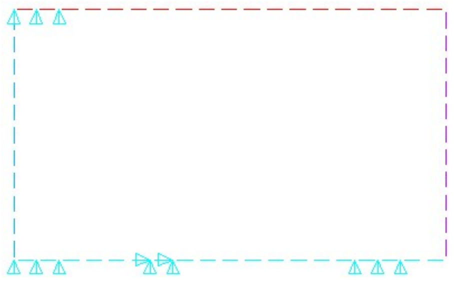

Figure 29. Constraints of the Optimized Rotating Ring

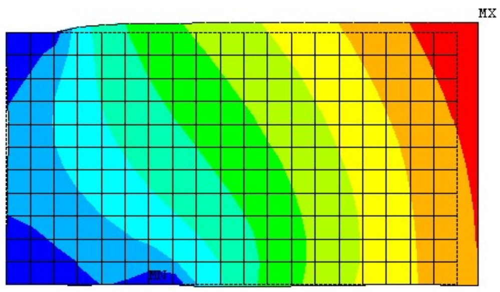

Figure 30. Thermal Deformation of the Optimized Rotating Ring

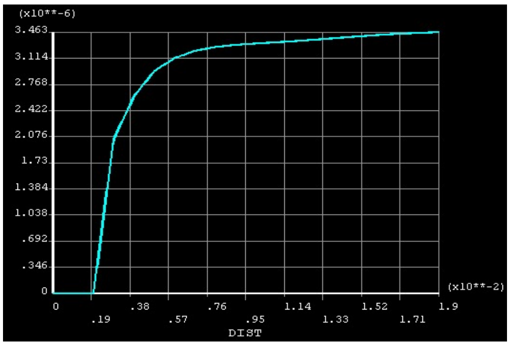

Figure 31. End Face Axial Deformation of the Optimized Rotating Ring

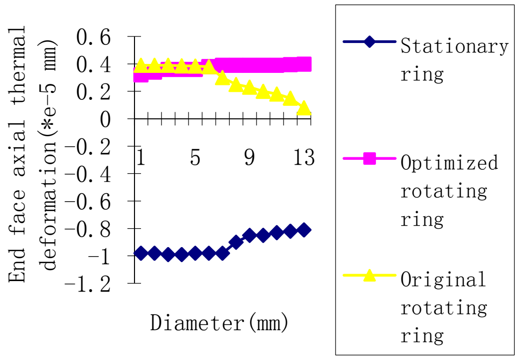

Figure 32. End Face Axial Deformation of the Rotating and Stationary Rings

Compare Figure 30 and Figure 31 with Figure 4 and Figure 5, the end face axial thermal deformation of the optimized rotating ring tends to smoothly, so the end face convergence conical angle of rotating ring is reduced. The end faces between the rotating and stationary rings tend to parallel.

5. Conclusions

Because of the thermal-structure coupling deformation of rotating and stationary rings, a convergent wedge which is in favor of gas film formation is formed between the end faces. But it results in an increase in leakage quantity. In addition, because of the oversize thermal deformation conicity of rotating and stationary rings, the prompt increasing of end face relative position destroys the stability of gas film.

Rotating speed, thermal expansion coefficient and Poisson ratio are the main factors affecting the thermal deformation in hydrostatic pressure mechanical seal, the thermal conductivity almost has no effect on the thermal deformation.

By adjusting the constraints of the rotating ring or the stationary ring, the end face deformation form can be optimized, but this is not the only method.

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