Optimization design of turbo-expander gas bearing for a 500W helium refrigerator

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Abstract. Turbo-expander is the core machinery of the helium refrigerator. Bearing as the supporting element is the core technology to impact the design of turbo-expander. The perfect design and performance study for the gas bearing are essential to ensure the stability of turbo-expander. In this paper, numerical simulation is used to analyze the performance of gas bearing for a 500W helium refrigerator turbine, and the optimization design of the gas bearing has been completed. And the results of the gas bearing optimization have a guiding role in the processing technology. Finally, the turbine experiments verify that the gas bearing has good performance, and ensure the stable operation of the turbine.

1. Introduction
With the development of superconducting magnet in fusion devices and high energy accelerators, the large-scale helium refrigerator has been widely applied. The 500W@4.5K helium refrigerator for ADS (Accelerator Driven Subcritical) project has been designed and built at the Institute of Plasma Physics, Chinese Academy of Sciences (CAS), which could be used for the superconducting coils testing. And the ADS project was supported by the special fund for strategic pilot technology CAS [1]. The 500W helium refrigerator adopts the standard Claude refrigeration cycle, which has two turbo-expanders in series.

At present, many helium turbo-expanders for the refrigerators, which the supporting structures are all gas bearings, were produced by LINDE or AIR LIQUIDE Corporation. In order to improve the capability of independent innovation, our project team developed a helium turbine for the 500W helium refrigerator.

The cryogenic turbine is the core machinery of the refrigerator, which efficiency and reliability are crucial to the economical advantage and long-term stable operation for the refrigerator. The bearing as the supporting element is the core technology to impact the turbine stability. In cryogenic system, with the requirement of high rotation speed and efficiency, the lubrication performance between the rotor and gas bearing becomes the main factor affecting the performance of the rotating machineri es [2]. The optimization design and performance study for the gas bearing are essential to ensure the stability turbo-expander.

2. Gas bearing engineering design
The high rotation speed and cryogenic working are required by the helium turbo-expander, so it is necessary to choose the gas bearing, which has the performances such as light, non-polluting and cryogenic operation. The home-made helium turbine employs the static gas bearing, because of the
high capacity and mature technology [3]. In order to avoid the phenomenon of the bearing air-hammer, and reduce the processing difficulty, the inherent orifice is adopted. The rotation speed is more than 150krpm.

The impeller structure, rotation speed and power were obtained in the turbine design process. Through these parameters, the rotor diameter was calculated and a series of the approximately reasonable ratio of length to diameter (L/D) for bearing were determined. According to the experience of engineering design, the final structure of the bearing was gained. The radial gas bearing structure is shown as Figure 1 and 2. The bearing has two rows of orifice restrictors, each with 8 and uses "O" ring to increase stability. The parameters of the radial gas bearing are summarized in Table 1.

![Figure 1. Radial gas bearing structure](image1)

![Figure 2. 3D model of radial static gas bearing](image2)

### Table 1. Geometric Parameters of the gas bearing

| Parameter                  | Values  |
|----------------------------|---------|
| Bearing diameter           | D=17mm  |
| Bearing length             | L=28mm  |
| Hole to edge distance      | h1=7.25mm|
| Inlet hole diameter        | a=2mm   |
| Inlet hole depth           | b1=2.5mm|
| Restrictor depth           | b2=1.5mm|
| Orifice rows               | 2       |
| Orifice number in one row  | 8       |

3. Optimization design method
The pressure field distribution of the narrow gas film is obtained to calculate the bearing characteristics by solving the Reynolds equation. At present, CFD numerical simulation has been widely applied to the performance analysis of the gas bearings. In this paper, the performance study and optimization design have been presented by using Fluent.

The Fluent method would not only accurately predict the flow state, but also correct the problems in the engineering design to achieve the gas optimization design. CFD simulation doesn’t need to write programs, which could shorten the design cycle and improve the design reliability [4].

Because of the good convergence effect, the laminar flow model has been adopted. The numerical model is assumed as following: 1) The surface roughness of the bearing is neglected, and the clearance is constant. 2) Nitrogen is selected as the lubrication medium, which is set as the ideal gas. 3) The outlet pressure is the atmospheric pressure, and the flow process is an adiabatic process.

4. Numerical simulation

4.1. Calculation model
Figure 3 shows that the bearing flow field is the symmetrical distribution and the maximum pressure is at the minimum of the gas film. Therefore, the 1/4 model is adopted to simplify calculation. The gas film is very narrow, which is only 10-30μ, and its thickness is three orders of magnitude smaller than the radial of the bearing. So considering the mesh number and the calculation accuracy, ten layers of
the mesh are selected in the thickness of the gas film. The flow field is divided into many parts for meshing, and the meshes are basically hexahedral structure (HEX), as shown in Figure 4. There are four kinds of boundary conditions in the calculation model: 1) Inlet pressure of gas supply holes; 2) pressure outlet of the gas film; 3) Symmetry surface; 4) Wall surface.

Figure 3. Pressure distribution of the gas bearing

Figure 4. Mesh

4.2. Results and discussion
The bearing load capacity, stiffness and gas consumption are analyzed by changing the gas supply pressure, eccentricity, gas hole diameter and clearance, and the corresponding relationship have been obtained. All the study are the theoretical basis for the design and optimization of the gas bearing, and provide the stability guarantee for the helium turbo-expander.

4.2.1 Effect of gas supply pressure variation. The simulation model is listed in Table 2, where the geometric parameters, eccentricity, and radius clearance are fixed values. Figure 5 and Figure 6 show that, with the increase of gas supply pressure, the bearing load capacity W, stiffness K and gas consumption Q are gradually increasing.

As shown in Figure 3, the gas bearing generates load capacity because of the pressure difference between the large and the small film. When the supply pressure increases, the pressure after the orifices is increasing, but the outlet pressure remains constant, so the pressure difference of the film increases. Then the capacity of the bearing strengthens.

Table 2. Simulation model for gas supply pressure variation

| eccentricity | clearance | hole diameter | supply pressure |
|--------------|-----------|---------------|-----------------|
| ε=0.5        | Cr=0.015 mm | d=0.3 mm, 0.4 mm, 0.5 mm | P=6, 8, 10, 12, 14, 16, 18, 20 bar |

The increase of gas consumption Q will increase the power consumption of the helium compressor, and reduce the COP value of the whole operation of the helium refrigerator. At the same time, the supply pressure is also limited by the outlet pressure of the compressor. So the supply pressure P couldn’t be increased with no restriction. According to the actual conditions of the helium turbo-expander and the experimental conditions of the bearings, 10 bar supply pressure will be adopted.

Figure 5. Relationship between bearing load capacity, gas consumption and gas supply pressure

Figure 6. Relationship between stiffness and gas supply pressure
4.2.2. Effect of eccentricity variation. The simulation model is listed in Table 3, where the geometric parameters, hole diameter and supply pressure are fixed values. Figure 7 and Figure 8 show the effect of the eccentricity on the bearings performance. With the eccentricity increase, the bearing load capacity \( W \) is gradually increasing, and gas consumption \( Q \) is slightly reducing.

| Simulation models for eccentricity variation |
|---------------------------------------------|

| hole diameter | supply pressure | clearance | eccentricity |
|---------------|-----------------|------------|--------------|
| d=0.3 mm | P=10 bar | Cr=0.015 mm, 0.02 mm, 0.025 mm | \( \varepsilon =0.1,0.2,0.3,0.4,0.5 \) |

The difference in gas film thickness is due to eccentricity, which leads to difference of the gas-flow resistance. With the increase of the eccentricity, the flow resistance is increasing at the minimum of the gas film, and the film pressure increases after the restrictor. On the contrary, the flow resistance is decreasing at the maximum of the gas film, and the film pressure decreases after the restrictor. So the pressure difference of the gas film increases, then the bearing load capacity \( W \) strengthens.

![Figure 7. Relationship between bearing load capacity, gas consumption and eccentricity](image1)

![Figure 8. Relationship between stiffness and eccentricity](image2)

4.2.3. Effect of hole diameter variation. The simulation model is listed in Table 4, where the geometric parameters, eccentricity and supply pressure are fixed values. Figure 9 and Figure 10 show the effect of the hole diameter on the performance of the bearings.

| Simulation models for hole diameter variation |
|---------------------------------------------|

| eccentricity | supply pressure | clearance | hole diameter |
|--------------|-----------------|-----------|---------------|
| \( \varepsilon =0.5 \) | P=10 bar | Cr=0.015 ,0.02 ,0.025 ,0.03 mm | d=0.1-0.5 mm(interval 0.05mm) |

With the increase of the hole diameter, the bearing load capacity and the stiffness increase first and then decrease, there is an optimum diameter. The gas consumption increases because of the increase of the gas flow area. The smaller hole will lead to difficulty in processing, which tend to clog up because of the gas impurities. After considering various factors and the actual situation, the smaller diameter is properly adopted.
4.2.4. Effect of clearance variation. The simulation model is listed in Table 5, where the geometric parameters, the eccentricity and supply pressure are fixed values. Figure 11 and Figure 12 show the effect of the clearance on the performance of the bearings.

Table 5. Simulation models for clearance variation

| eccentricity | supply pressure | hole diameter | clearance |
|--------------|-----------------|---------------|-----------|
| ε=0.5        | P=10 bar        | d=0.3,0.4,0.5mm | Cr=0.01 ,0.012 ,0.015 ,0.017,0.02,0.022, 0.025,0.027,0.03,0.032,0.035,0.04mm |

With the increase of the clearance, there is a maximum value of the bearing load capacity at Cr=0.017mm, but the load capacity and stiffness decrease dramatically at Cr<0.015. If the maximum capacity is required, the clearance at the maximum value of the load capacity can be selected. When the clearance increases, the distance between the bearing and the shaft will become larger, so the load capacity and stiffness decrease. The gas consumption Q increases with the increase of the clearance. In a word, the optimum clearance should be chosen at the maximum bearing load capacity or less than Crm.

5. Ambient temperature test
The helium turbo-expander and its gas bearings have completed the design and machining, also have performed ambient temperature testing several times at the laboratory test platform. The high pressure nitrogen has been used in the testing the same as the numerical simulation. The results of numerical simulation guide the machining and assembly, and the bearing performance has been verified at ambient temperature test.
Figure 13 is the axle centre trail of the bearing in the test. The rotation speed of the turbine is 158 krpm, and the maximum amplitude is only 7~10 μm. The gas bearing has good stability and the mechanical properties of the turbo-expander get the requirements.

![Figure 13. Axle centre trail of bearing](image)

**6. Conclusions**

In the paper, through the Fluent numerical simulation, the static performance of the turbine radial gas bearing for 500 W helium refrigerator has been studied. The bearing load capacity, stiffness and gas consumption are analyzed by changing the geometric and assembly parameters, and the corresponding relationship have been obtained. With increasing the gas supply pressure and eccentricity, reducing hole diameter and adjusting the clearance between the bearing and the rotor, the bearing load capacity and stiffness can increase. At last, the stability of the home-made bearing is verified by the ambient temperature testing.

**References**

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