Numerical research on sealing performance of high speed and high pressure centrifugal compressor seal

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Abstract. In this paper, two seal schemes of stepped labyrinth seal and straight through-hole seal are selected for the shaft end seal of S-CO2 centrifugal compressor with the output of 100kW. The full three-dimensional CFD numerical simulation method is adopted to analyze and compare the sealing characteristics of two S-CO2 seals in S-CO2 centrifugal compressor under different outlet back pressures and sealing gaps. The results show that the leakage flow rate of S-CO2 stepped labyrinth seal and through-hole seal increases with the decrease of back pressure. The leakage flow rate of the stepped labyrinth seal and the through-hole seal reaches the corresponding critical value when the back pressure is 1.0 MPa and 3.0 MPa respectively. The critical leakage flow rate of the stepped labyrinth seal and the through-hole seal under the condition of 0.1 mm sealing gap is 0.158 kg/s and 0.128 kg/s respectively. Compared to the through-hole seal, the stepped labyrinth seal can withstand greater pressure differentials at the same sealing gap and has superior S-CO2 sealing performance.

1. Introduction

Due to the high density, low viscosity and low critical point parameters of the S-CO2 working fluid, the S-CO2 Brayton cycle power system can achieve the goal of simultaneous optimization of efficiency, weight and volume. The S-CO2 compressor is the core equipment for the system thermal power conversion process. The harsh environment of high pressure difference, high density, high speed and complex physical properties will cause problems such as leakage, blast loss, flow excitation and wear failure of the S-CO2 compressor shaft end seal. As a key component of the S-CO2 compressor, the shaft end seal controls the leakage flow of the working fluid at the gap passage between the rotor and stator of the compressor. Moreover, the unsteady airflow excitation force at the seal has a significant impact on compressor operating efficiency and operational stability[1-3].

Limited to complex experimental conditions and severely varying physical parameters, the traditional experimental measurement methods and numerical prediction methods have been greatly challenged in the field of S-CO2 compressor sealing technology. At present, there are relatively few experimental and numerical studies on the leakage characteristics of compressor shaft end seals in the S-CO2 operating environment. SANDIA National Laboratory evaluates the sealing performance of at least 16 labyrinth seals in a 125kW S-CO2 turbomachinery component performance test rig. It is finally determined that the stepped labyrinth sealed with a floating wearable static ring can meet the sealing requirement[4].

In this paper, the scheme design of stepped labyrinth seal and straight through-hole seal is performed for the S-CO2 centrifugal compressor with the output of 100kW. The full three-dimensional
CFD numerical method is adopted to analyze and compare the sealing performance of two S-CO₂ shaft end seals under different outlet back pressures and sealing gaps.

2. Scheme design of the S-CO₂ compressor shaft end seal

Based on the main installation dimensions of the compressor shaft end seal shown in Figure 1 and Table 1, two seal schemes of stepped labyrinth seal and straight through-hole seal are designed separately.

![Figure 1. Schematic diagram of the S-CO₂ compressor rotor.](image1)

| Number | Variable                              | Unit       | Value |
|--------|---------------------------------------|------------|-------|
| 1      | Working fluid type                    | —          | S-CO₂ |
| 2      | Inlet pressure of the shaft end seal  | MPa        | 12.0  |
| 3      | Inlet temperature of the shaft end seal | °C         | 100   |
| 4      | Shaft diameter                        | mm         | 30    |
| 5      | Rotational speed                      | r/min      | 30000 |

2.1. Stepped labyrinth seal

The labyrinth seal has the advantages of simple structure, low cost, convenient installation and replacement, and large tolerance to changes in heat and pressure difference. It has been widely used in turbomachinery. Figure 2 shows the schematic diagram of the S-CO₂ stepped labyrinth seal. Table 2 shows the labyrinth seal geometry parameters. Considering the installation size requirements, the stepped labyrinth seal is designed with the axial length of 52 mm and the diameter of 30 mm. The stepped labyrinth seal has 12 sealing teeth. The height of the upstream step of each tooth is 0.5 mm. Two sealing gaps of 0.1 mm and 0.2 mm are designed to study the influence of the sealing gap on the sealing performance.

![Figure 2. Schematic diagram of the stepped labyrinth seal structure.](image2)
2.2. Through-hole seal

In order to achieve the purpose of improving the dynamic characteristics of flow excitation, the through-hole seal has a large roughness by changing the surface of the smooth stator. The round holes in the through-hole seal are machined on the metal material by a milling cutter or an electric spark. Therefore, it has the advantages of simple manufacturing process, low cost, good structure controllability, and wear resistance. Figure 3 shows the schematic diagram of the S-CO$_2$ through-hole seal. Table 3 shows the through-hole seal geometry parameters. Considering the installation size requirements, the through-hole seal is designed with the axial length of 60 mm and the diameter of 30 mm. The number of axial holes is 23 and the number of holes is 1150. Two seal gaps of 0.1 mm and 0.2 mm are designed to study the influence of the seal gap on the sealing performance.

![Schematic diagram of the through-hole seal structure.](image)

Table 3. Geometry parameters of the through-hole seal.

| Number | Variable                              | Unit   | Value |
|--------|---------------------------------------|--------|-------|
| 1      | Length of the seal                    | mm     | 60    |
| 2      | Radial gap                            | mm     | 0.1/0.2 |
| 3      | Hole diameter                         | mm     | 2.0   |
| 4      | Hole depth                            | mm     | 2.0   |
| 5      | Distance between the centre of adjacent holes | mm     | 2.5   |
| 6      | Number of holes                       | —      | 1150  |
| 7      | Number of axial holes                 | —      | 23    |
3. Numerical calculation model and method for shaft end seal

3.1. Numerical calculation model
Figure 4 and figure 5 show three-dimensional computational grids of the labyrinth seal and the through-hole seal. The software ICEM CFD is applied to generate the multi-block structured grid for the shaft end seal. A total of 25-35 nodes are arranged at the sealing gap. Based on the leakage flow rate, the numerical calculation model is tested for grid independence. Finally, the number of mesh nodes for the labyrinth seal and the through-hole is 640,000 and 1.64 million respectively.

3.2. Numerical calculation method
The RANS equation is solved numerically using the commercial software ANSYS-CFX 16.0. The total pressure and total temperature are set at the inlet and the average static pressure is set at the outlet. The SST turbulence model is selected for the labyrinth seal and the through-hole seal calculation. The solid walls are all set to a smooth adiabatic boundary, and the near wall is treated by the improved wall function method. The labyrinth seal and the through-hole seal are solved in the static domain, and the rotor surface is set to the rotational speed of 30,000 rpm.

In order to evaluate the validity and accuracy of the numerical method for the prediction of the leakage characteristics, the S-CO$_2$ labyrinth seal test piece with two seal teeth in the literature [5] is analyzed. The leakage flow rate at 13 pressure ratios (0.3 - 0.9) is calculated and compared with the experimental results for an inlet pressure of 10 MPa, a temperature of 55 °C, and a rotational speed of 0 rpm. The results show that the numerical method used in this paper can accurately predict the leakage characteristics of the S-CO$_2$ labyrinth seal. The leakage prediction error is less than 6%.

4. Numerical result analysis of the sealing performance for shaft end seal

4.1. Stepped labyrinth seal
Figure 6 shows the variation of the stepped labyrinth seal leakage flow rate with back pressure under different sealing gaps. The leakage flow rate of the labyrinth seal increases as the back pressure decreases. When the seal gap increases from S = 0.1 mm to S = 0.2 mm, the critical leakage flow rate of the labyrinth seal increases from 0.158 kg/s to 0.265 kg/s.

Figure 6. Variation of labyrinth seal leakage flow rate with back pressure.
When the labyrinth seal back pressure is reduced to 3.0 MPa, the local area near the rotor surface at the last seal tooth gap reaches the critical flow state ($Ma = 1.0$). When the labyrinth seal back pressure is further reduced to 1.0 MPa, the last seal tooth gap is completely occupied by the supersonic flow. The flow reaches the critical state and the leakage flow rate reaches its maximum.

4.2. Through-hole seal

Figure 11 shows the variation of the through-hole seal leakage flow rate with back pressure under different sealing gaps. The leakage flow rate of the through-hole seal increases as the back pressure decreases. When the seal gap increases from $S = 0.1$ mm to $S = 0.2$ mm, the critical leakage flow rate of the through-hole seal increases from 0.128 kg/s to 0.330 kg/s. When the through-hole seal back pressure is further reduced to 3.0 MPa, the last seal tooth gap is completely occupied by the supersonic flow. The flow reaches the critical state and the leakage flow rate reaches its maximum.
According to the above analysis, it can be concluded that the S-CO$_2$ through-hole seal has better sealing performance than the S-CO$_2$ labyrinth seal at a small sealing gap (0.1 mm). The labyrinth seal has better sealing performance at larger sealing gap (S = 0.2 mm). The labyrinth seal can withstand greater pressure differentials at the same sealing gap. As a result, the stepped labyrinth seal has superior S-CO$_2$ sealing performance compared to the through-hole seal. Considering the dynamic characteristics of the seal flow excitation under high inlet pre-rotation conditions, the S-CO$_2$ compressor shaft end seal scheme can consider the combination of the stepped seal tooth rotor with the sealing hole stator to achieve low leakage and high damping sealing performance.

5. Conclusions
In this paper, the scheme design of stepped labyrinth seal and straight through-hole seal is performed for the S-CO$_2$ centrifugal compressor. Moreover, the sealing performance of two S-CO$_2$ shaft end seals under different outlet back pressures and sealing gaps are analyzed. The main conclusions are as follows:

1) The critical leakage flow rate of the labyrinth seal increases from 0.158 kg/s to 0.265 kg/s as the seal gap increases from 0.1 mm to 0.2 mm. The critical leakage flow rate of the through-hole seal increases from 0.128 kg/s to 0.330 kg/s as the seal gap increases from 0.1 mm to 0.2 mm.
2) The stepped labyrinth seal has superior S-CO$_2$ sealing performance compared to the through-hole seal.
3) In order to achieve the requirements of low leakage and high damping sealing performance, the S-CO$_2$ compressor shaft end seal scheme can consider the combination of the stepped seal tooth rotor with the sealing hole stator.

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