Numerical study on sealing performance of supercritical carbon dioxide compressor dry gas seal

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Abstract. Aiming at the serious problem of gap leakage between the stator and rotor of the supercritical carbon dioxide compressor, the dry gas seal scheme for centrifugal compressor of small S-CO₂ power system is designed in this paper. The sealing characteristics of the single-stage spiral groove dry gas seal in the S-CO₂ operating environment are studied by the large-scale commercial CFD numerical analysis software ANSYS CFX. The leakage characteristics of the S-CO₂ dry gas seal at different film thicknesses are obtained. The results show that the S-CO₂ dry gas seal leakage flow rate increases linearly with the increase of the film thickness. The dry gas seal leakage flow rate under different film thickness is 0.04%~0.45% of the S-CO₂ compressor flow rate, which can meet the leakage requirements of the centrifugal compressor shaft end seal in the small S-CO₂ power system.

1. Introduction
High pressure, high speed, small size and high energy density bring serious leakage loss problem of the gap between the stator and rotor to S-CO₂ turbomachinery, which imposes very stringent design requirements on the performance of the seal. Conventional turbomachinery sealing schemes such as labyrinth seal, honeycomb seal, brush seal and bag type seal are difficult to meet the requirements for efficient and stable operation of the S-CO₂ turbine and compressor [1,2]. Therefore, it is necessary to carry out research on the leakage characteristics of the seal in the S-CO₂ operating environment and develop high performance sealing technology for S-CO₂ turbomachinery.

The fluid-thermal-solid coupling numerical analysis of a 10MW S-CO₂ turbine shaft end dry gas seal is conducted by General Electric Company [3]. Further, the influence of film thickness, pressure ratio and end face structure on the stiffness of S-CO₂ dry gas seal film is measured by D Trivdei et al [4]. A Rimpel et al. [5,6] of the United States Southwest Research Institute built a 100-megawatt S-CO₂ power unit full-size dry gas seal test rig to verify the sealing performance of the large shaft diameter S-CO₂ dry gas seal.

In summary, turbomachinery seal in the S-CO₂ environment is still an emerging technology and faces many problems to be solved. Design and analysis of S-CO₂ dry gas seal is an important part of the S-CO₂ turbomachinery development process. The S-CO₂ dry gas seal scheme for the single-stage centrifugal compressor shaft end seal in the small S-CO₂ power system is designed in this paper. The full three-dimensional CFD numerical method is applied to analyze the sealing characteristics of the single-stage spiral groove dry gas seal in the S-CO₂ operating environment.
2. Scheme design

The dry gas seal is a non-contact dynamic seal that opens various shapes of fluid channels on the seal end face based on the gas thrust bearing technology. The spiral groove dry gas seal has the advantages of stable gas film, low leakage and long service life. It is widely used in petrochemical turbomachinery. The scheme design of the single-stage centrifugal compressor shaft end seal in the small S-CO\(_2\) power system is carried out in this paper. The rotational speed is 30000 r/min. The shaft diameter of the seal is 30 mm. The axial length of the seal is 60 mm. The seal inlet pressure is 12.0 MPa. The seal inlet temperature is 100°C. The seal outlet pressure is 0.1 MPa.

![Schematic diagram of the S-CO\(_2\) dry gas seal structure.](image1)

![Moving ring of the dry gas seal.](image2)

| Number | Variable                        | Unit    | Value |
|--------|---------------------------------|---------|-------|
| 1      | Inner radius                    | mm      | 30    |
| 2      | Outer radius                    | mm      | 40    |
| 3      | Spiral groove root radius       | mm      | 35    |
| 4      | Spiral angle                    | \(^{\circ}\) | 15    |
| 5      | Number of spiral grooves        | —       | 12    |
| 6      | Spiral groove depth             | mm      | 5     |
| 7      | Sealing gap/Film thickness      | \(\mu\)m | 3.0, 5.0, 7.0, 10.0 |

Figure 1 and Figure 2 show the structure of the dry gas seal. There are 12 spiral dynamic pressure grooves in the S-CO\(_2\) dry gas seal moving ring. Table 1 shows the geometric parameters of the dry gas seal. In order to study the effect of sealing gap on the sealing characteristics of S-CO\(_2\) dry gas seal, four kinds of sealing gaps with 3.0\(\mu\)m, 5.0\(\mu\)m, 7.0\(\mu\)m and 10.0\(\mu\)m are selected.
3. Numerical calculation model and method

3.1 Numerical calculation model
In order to facilitate the display of the dry gas seal spiral groove structure and the gas film gap, the S-CO$_2$ dry gas seal three-dimensional calculation model and the three-dimensional calculation mesh in Fig. 3 are magnified 1000 times in the gap and groove depth directions. Due to the rotational period symmetry of the dry gas seal structure, a single spiral groove arc is selected as the calculation domain. Rotating periodic boundaries are applied on both sides of the spiral groove arc in the circumferential direction. The multi-block structured grid is applied to mesh the calculation domain. The grid-independent verification calculation of the model is completed with the leakage flow rate as the evaluation index. The dry gas seal calculation model uses 1.63 million grid nodes.

![Figure 3. S-CO$_2$ dry gas seal calculation model and grid.](image)

3.2 Numerical calculation method
The large commercial CFD numerical analysis software ANSYS CFX is adopted to solve the RANS equation. The inlet sets the total pressure and total temperature boundary conditions. The outlet sets the average static pressure boundary condition. The flow in the dry gas seal film gap is laminar. The convection term uses the high-precision discrete format. The solid wall is set to a smooth adiabatic boundary condition. The near wall is treated by an improved wall function method. The dry gas seal calculation model is solved in the rotating domain. The static ring end face is given a reverse rotation speed of -30000 r/min.

4. Results analysis
Figure 4 and Figure 5 show the variation of S-CO$_2$ dry gas seal leakage and opening force with film thickness.

![Figure 4. Dry gas seal leakage flow rate under different film thicknesses.](image)

![Figure 5. Dry gas seal opening force under different film thicknesses.](image)
The dry gas seal utilizes the fluid dynamic pressure effect in the spiral groove during actual operation to form a gas film having certain stiffness at the seal end face. Thereby, the static ring and the moving ring are separated to achieve non-contact gas lubrication. The thickness of the gas film is the size of the sealing gap, which is the channel for leakage of the S-CO\textsubscript{2}. It has a significant impact on the leakage characteristics of the dry gas seal. It can be seen from the figure that the dry gas seal leakage flow rate increases linearly with the increase of the gas film thickness, and the opening force decreases with the increase of the gas film thickness. The dry gas seal leakage flow rate is 0.04\% to 0.45\% of the centrifugal compressor flow rate in the small S-CO\textsubscript{2} power system. According to the one-dimensional analysis model of R A Bidkar et al. [7], the dry gas seal can meet the leakage requirement of the shaft end seal of the S-CO\textsubscript{2} compressor.

![Figure 6. Radial variation curve of dry gas seal end face pressure under different film thicknesses.](image)

It can be seen from figure 6 that the S-CO\textsubscript{2} pressure in the dry gas seal spiral groove of each gas film thickness is gradually reduced from the outer radial to the inner diameter. It indicates that the dynamic pressure effect of the spiral groove is weak. The spiral groove structure in the dry gas seal of this paper is based on the optimization result of air lubrication working fluid. There is still a large optimization space for the S-CO\textsubscript{2} lubricating working fluid, which can further reduce the leakage flow rate of the compressor.

5. Conclusions
The scheme design of dry gas seal is performed for the S-CO\textsubscript{2} centrifugal compressor in the small S-CO\textsubscript{2} power system. A full three-dimensional CFD numerical model is constructed. The sealing characteristics of S-CO\textsubscript{2} dry gas seal under different film thicknesses are analyzed. The main conclusions are as follows:

1) The S-CO\textsubscript{2} dry gas seal leakage flow rate increases linearly with the increase of the film thickness, and the opening force decreases with the increase of the gas film thickness. The dry gas seal leakage flow rate under different film thickness is 0.04\%~0.45\% of the S-CO\textsubscript{2} compressor flow rate, which can meet the requirements of the centrifugal compressor shaft end seal in the small S-CO\textsubscript{2} power system.

2) The S-CO\textsubscript{2} pressure in the dry gas seal spiral groove of each gas film thickness gradually decreases from the outer radial to inner diameter. The dry gas seal structure optimization design under S-CO\textsubscript{2} lubrication conditions can be further developed to reduce the dry gas seal leakage flow rate and improve the efficiency of the S-CO\textsubscript{2} power system.
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