The Influence of the Clearance on Performance of Compressor

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Abstract. Cold compressor (CC) was adopted to pump saturated liquid helium to obtain subcooled helium. In the Experimental Advanced Superconducting Tokamak (EAST) system, cold presses were studied and would replace the oil ring pump. The cold compressor processing and installation had been completed, and it had been tested by cold nitrogen gas. For cold compressors, testing at low temperature was essential, but the real working condition of low-temperature helium gas had great risks for large helium cryogenic system. Therefore, an independent cold nitrogen test system was an economical solution. In this work, numerical simulation and quantitative analysis method were used to investigate the flow field around different tip clearances and mass flow by CFD at liquid nitrogen temperature, and they were validated by experiments. When the tip clearance was increased by 0.1mm, the pressure ratio dropped 0.27% and the polytropic efficiency dropped 0.82%. To a certain extent, a larger tip clearance could improve the surge condition and had little influence on the efficiency. Therefore, in the design and operation, the tip clearance could be appropriately increased.

1. Introduction

Tip clearance flow, under the influence of clearance size and rotating speed, reduces the pressure ratio and efficiency of the compressor [1]. Galindo [2] found when the tip clearance decreased, the pressure ratio increased and the efficiency increased, but the acoustic characteristics of the compressor did not change obviously. Drgan [3] found that stage performance tended to be correlated with tip clearance, while the factors affecting rotor performance were more complex. Denton [4] and Liu [5] determined that tip clearance flow was one of main sources of loss in the compressor. Furthermore, Senoo [6] and Teemu [7] found that tip clearance flow loss was proportional to clearance size. Nili-Ahmadabadi [8] determined that the increment of the tip clearance from 0 to 1 mm resulted 20% efficiency decrease. The influence of clearance on flow evolution in diffuser of a centrifugal compressor under partial load was investigated by Schleer [9], whereas Yamada [10] compared tip clearance flow fields in two types of transonic centrifugal compressor impellers with splitter blades. Dambach [11] and Berdanier [12] also completed a notable experimental study on tip clearance flow and multistage compressor. Four kinds of flow patterns (blade wake, jet, channel wake, and tip clearance flow) were observed at the impeller discharge plane by Hong [13]. Small tip clearance changed and the related performance changed which occur as a result of changes to ambient temperature were typically considered negligible.

In the initial stage, the real working condition of cold helium gas had great risks for large helium cryogenic system. Therefore, an independent cold nitrogen test system was an economical solution. As
preparation work, the CC should be run at liquid nitrogen temperature. In this work, numerical simulation and quantitative analysis method were used to investigate the flow field around different tip clearances and mass flow by CFD at liquid nitrogen temperature, and they were validated by experiments. In the process of numerical simulation, a variety of turbulence models were available, including k- $\varepsilon$, RNG k- $\varepsilon$, SST and so on. For rotating machinery, k- model could be selected for calculation with better accuracy and relatively smaller computation.

2. Design and numerical model of the CC
As a substitute, cold compressors have obvious advantages. Table 1 shows the comparison between cold compressor and warm compressor. The design of the CC is depicted in Figure 1. It includes a motor with water cooling operational at ambient temperature to maintain the stability of the electronic system. Figure 1 illustrates the inlet pipes, shroud, impeller, diffuser, volute, heat insulation material with thermal anchor, and hollow motor shaft in a vacuum container. Figure 2 depicts the cartridge of the CC.

Table 1. Comparison between cold compressor and warm compressor in EAST

|                     | Warm compressor | Cold compressor |
|---------------------|-----------------|-----------------|
| Volume flow (m³/h)  | 3000            | 25.6            |
| Power (kW)          | 90              | <2              |
| Discharge temperature (K) | 293            | ~5              |
| Noise (dB)          | 90              | <50             |
| Mass (kg)           | 630             | 40              |
| Refrigerating capacity at 3.5 K (W) | 1050           | 1050            |

![Figure 1. Sectional drawing of the CC](image)

1-Motor, 2-Bolt(G10), 3-Heat insulation, 4-Thermal anchor, 5-Volute, 6-Impeller, 7-Inlet, 8-Motor shaft
The parameters of CC are shown in table 2. A single-passage model is shown in figure 3 for numerical calculation, and figure 4 considers the grid independence. The inlet mass, total temperature and outlet static pressure are given as boundary conditions in CFX.

| Table 2. The parameters of CC and mesh |
|---------------------------------------|
| Impeller diameter/mm | 100 | Shroud diameter/mm | 54 |
| Impeller outlet tip width/mm | 6 | Number of blades | 18 |
| Rotate speed/rpm | 18,000 | Tip clearance/mm | 0-0.6 |
| Mesh number | 340,000 | Average y+ | 4 |

Figure 2. CC cartridge

Figure 3. Mesh of the impeller
The flow inside the centrifugal compressor satisfies the conservation equation of mass, momentum and energy. Under stable working condition, the flow inside the centrifugal compressor is simplified to a steady state process. The following governing equation is established. For rotating machinery, the k-e model could be selected for calculation with better accuracy and relatively smaller computation.

Conservation of mass,
\[ \frac{\partial \rho}{\partial t} + \text{div}(\rho \mathbf{u}) = 0 \]  \hspace{1cm} (1)

Where \( \rho \) is density, \( t \) is time, \( \mathbf{u} \) is velocity vector.

Conservation of momentum,
\[ \rho \frac{\partial \mathbf{u}}{\partial t} = \rho F_b + \text{div} P \]  \hspace{1cm} (2)

Where \( P \) is pressure, \( F_b \) is force.

Conservation of energy,
\[ \frac{\partial}{\partial \tau} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z} = \alpha (\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2}) \]  \hspace{1cm} (3)

Where \( \alpha \) is thermal diffusivity, \( u, v, w \) are velocity component.

3. Different tip clearance effects on performance of CC by numerical simulation

Figure 5 depicts the pressure ratio versus \( m \) for different values of tip clearance.

![Figure 5. Pressure ratio versus m for different values of tip clearance of CC](image)

As shown in figure 5, the 0mm tip clearance, with highest pressure ratio, is an ideal condition. As the clearance increases, the efficiency shows a downward trend, and the highest efficiency point moves...
to the left, which means that a larger clearance has better surge characteristics and the cold compressor is more adaptable to complex conditions. However, this may also lead to the failure of the pressure ratio to meet the design requirement.

Figure 6 shows the pressure ratio versus tip clearance for different m.

![Figure 6. Relationship between pressure ratio and tip clearance for different m](image)

As shown in Figure 6, under different mass flow rates, the relationship between pressure ratio and tip clearance is approximately linear. However, when the flow rate is too small, such as 40g/s, the linear relationship does not satisfy, which means that the compressor may experience surge. It should be noted that different compressors are affected by the tip clearance differently.

As shown in Figure 7, the smaller the clearance, the more obvious the influence of flow rate on efficiency. The CC efficiency is high enough when the mass flow near the design point. Therefore, considering the pressure ratio, efficiency and surge characteristics, the 0.2mm tip clearance is considered appropriate.

![Figure 7. Relationship between polytropic efficiency and m for different values of tip clearance](image)

Figure 8 depicts the contour of relative Mach number at outlet of impeller for different values of tip clearance at 100 g/s, and all of the legends are unified. As shown in Figure 8, obviously, tip clearance flow decreases the value of velocity, with the increase of the tip clearance, the pressure and the efficiency gradually decreases.
4. Experimental investigation of CC tip clearance

4.1. Experiment apparatus

The experiment model is shown in figure 9. The liquid nitrogen tank is a double layers cylinder, and foam material is filled between the layers. About 200L liquid nitrogen is infused into tank, it will be evaporated by the heater at the bottom of tank. The mass flow rate of cold gas is controlled by the power of heater, and the height of liquid nitrogen level is between sensors pt100 (liquid) and pt100 (gas). The CC with 0.2 mm tip clearance impeller and 0.6mm tip clearance impeller are chosen to be tested. The Pin, Pout, Tin, Tout of impeller and liquid nitrogen temperature are measured. When using cold nitrogen as working fluid, in order to decrease the heater power, the rotating speed is 18000 rpm while the design point of CC for cold helium is 24000 rpm and 2.2 to 2.3 pressure ratio. According to the results of numerical simulation in figure 5 and figure 7, the maximum mass flow rate is 0.32kg/s when 18000rpm, which means 64 kW input power to evaporate liquid nitrogen, it’s difficult and unsafe to experiment apparatus. The actual heater power is 22kW and the measured mass flow rate is less than 0.11 kg/s. In future liquid helium experiments, this will be better, since the latent heat of vaporization of helium is much smaller. Experiment apparatus are shown in figure10.
4.2. Surge line of CC

The surge line of CC (tip clearance is 0.2 mm) is shown in figure 11. The experiments are divided into 6 groups according to mass flow rate from 10 g/s to 60 g/s. In every group, the speed is slowly increased until the CC surges.

![Surge line of CC (Tip clearance is 0.2 mm)](image)

**Figure 11.** Surge line of CC (Tip clearance is 0.2 mm)

The comparison chart of surge lines of 0.2 mm and 0.6 mm is shown in figure 12, a larger tip clearance will obviously improve the surge margin, which means larger stable operating range.
Figure 12. Comparison chart of surge lines

4.3. Experimental results

Figure 13 depicts the comparison of numerical and measured pressure ratio. Compared with numerical data, in general, the pressure ratio of experimental data is 0.3%~1.4% lower, but the trend of the curve is consistent. When the value of tip clearance increases from 0.2mm to 0.6mm at 100 g/s, the numerical result shows that the pressure ratio decreases by 1.08%, and the experimental result is about 1.32%, which is in good agreement with numerical result.

Figure 13. Comparison of numerical and measured pressure ratio

Figure 14 depicts the comparison of numerical and measured polytropic efficiency. Compared with numerical data, the polytropic efficiency of experimental data is 0.6%~1.0% lower, but the trend of the curve is consistent. When the value of tip clearance increases from 0.2mm to 0.6mm at 100 g/s, the numerical polytropic efficiency decreases by about 3.28%, and the experimental date is 3.52%.
5. Conclusion
An increase in tip clearance results in a decrease in the pressure ratio and polytropic efficiency. In general, for the sample CC at 100 g/s mass flow rate, every 0.1mm increase in clearance corresponds to 0.27% decrease in pressure ratio and 0.82% decrease in polytropic efficiency.

Compared with numerical simulation results, the experimental pressure ratio and polytropic efficiency are lower, but the trend of the curve and the influence of tip clearance on performance are consistent. When the tip clearance is increased by 0.1mm at 100 g/s, the pressure ratio drops 0.33% and the polytropic efficiency drops 0.88%. What’s more, a larger tip clearance will obviously improve the surge margin and have larger stable operating range. To a certain extent, a larger tip clearance could improve the surge condition and had little influence on the efficiency. Therefore, in the design and operation, the tip clearance could be appropriately increased.

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