Helium turbines design and room temperature testing of a 500 W at 4.5 K refrigerator

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Abstract. The indigenous design and development of helium turbines of a 500 W / 4.5 K refrigerator have been started at the Institute of Plasma Physics, Chinese Academy of Sciences. This paper briefly discusses the design process and some of the fabrication drawings for the whole helium refrigerator with two helium turbines, which include the turbine wheel, nozzle, diffuser, shaft, brake compressor, two types of bearing, appropriate housing and all other parts. The helium turbines have been designed, manufactured and tested at room temperature. At room temperature, the test results are acceptable; the shaft vibration amplitude is less than 0.010 mm below 247 krpm. The low temperature testing will be carried out in the future.

1. Introduction

The expansion turbine constitutes the most critical component of a large number of cryogenic process plants like air separation units, helium liquefiers and low temperature refrigerators. The primary function of an expansion turbine is to produce the necessary refrigeration. This is obtained by expanding the process gas through the turbine where power is extracted from the fluid and enthalpy of the gas decreased. The use of turbines offers greater economy, higher efficiency, along with improved safety and flexibility as compared to reciprocating expanders. The schematic flow diagram of the 500 W / 4.5 K cryogenic system is shown in figure 1.
The helium turbine of a 500 W / 4.5 K cryogenic system employs two static gas bearings; one at the low temperature end and one at the warm end. The key parts of the turbines include the gas bearing chamber, the rotor (impellers and shaft), the nozzle, the diffuser, gas seals, the radial gas bearing, the thrust gas bearing, the speed indicator, low temperature parts and several adiabatic pieces. The drawing and the picture of the helium turbine are displayed in figure 2 and figure 3 respectively.

2. The design of the helium turbines

The cryogenic turbines used in this study were designed and developed for a 500 W / 4.5 K helium cryogenic system. The helium turbines were designed including the core parts, such as: journal and thrust gas bearings, the gas bearing chamber, shaft, brake compressor, diffuser, nozzle, turbine wheel, and some other adiabatic components. The design of the core parts are described in the following sections.

2.1 Turbine wheel design

The role of a turbine wheel is conversion of most of the kinetic energy of the process gas into mechanical energy. The design parameters and the design results are shown in table 1. Figure 4 is the design drawing of the expansion turbine wheel.
Table 1. The design parameters and design results of helium turbines

| Name | Pin (bara) | Pout (bara) | Tin (K) | Tout (K) | Eff. | Flowrate (g/s) | Speed (krpm) | Capacity (W) |
|------|------------|-------------|---------|----------|------|----------------|--------------|--------------|
| T1   | 12.4       | 6.0         | 34.5    | 28.46    | 69%  | 34.5           | 243          | 1098         |
| T2   | 5.6        | 1.2         | 13.5    | 8.89     | 68%  | 34.5           | 160          | 700.8        |

*a* The unit of the turbine speed, 1krpm = 1000 rpm.

Figure 4. The engineering drawing of Expansion Turbine Wheel.

2.2 Nozzle Design

The nozzle accelerates the fluid and directs it towards the turbine wheel blade. The entropy loss coefficient shows that the flow distortion within the nozzle has a major impact on the turbine efficiency and therefore the fluid should expand within the nozzle with minimum drop in total pressure. The design values are shown in table 2. Figure 5 is the drawing of the turbine nozzle.

Table 2. The nozzles configuration design results for helium turbines.

| Name | Out Dia. (mm) | Inner Dia. (mm) | Height (mm) | Throat Width (mm) | No. (pieces) |
|------|---------------|-----------------|-------------|-------------------|--------------|
| T1   | 39            | 17.5            | 2.0         | 1.2               | 10           |
| T2   | 40            | 20.6            | 1.95        | 1.38              | 10           |

Figure 5. The engineering drawing of turbine nozzle.

2.3 Shaft Design

The shaft should be designed on the basis that the rated speed is far from the critical speed, that it meets the maximum stress requirement and that its heat conduction is acceptable. Our approach,
however, has been to choose the dimensions based on data from comparable installations by other workers and to check for maximum stress, critical speed and heat conduction. We have taken a shaft of diameter of 12 mm and length 89 mm with a thrust collar of diameter 37 mm. The drawing of turbine shaft is shown in figure 6.

Figure 6. The engineering drawing of the turbine shaft.

2.4 Gas Bearing Design

Successful development of a turbine strongly depends on the performance of the bearings and their protection systems. We have used gas lubricated static bearings. The main advantages of these bearings are high stability against self-excitation and external dynamic load, and fewer constraints on fabrication, albeit at the cost of some process gas consumption.

The parameters of the radial gas bearing structure are summarized in table 3. The bearings have been designed assuming an eccentricity ratio of 0.5, a supply pressure of 12.0 bara and a discharge pressure of 1.5 bara. Based on the relevant data from the literature, we have computed the following parameters, are shown in table 3 for a journal bearing. The drawing of the turbine journal gas bearing is shown in figure 7.

Table 3. The design parameters of the journal gas bearing.

| Parameter               | Bearing diameter (mm) | Bearing length (mm) | Hole to edge distance (mm) | Inlet hole depth (mm) | Restrictor depth (mm) | Orifice number in one row |
|-------------------------|-----------------------|---------------------|---------------------------|-----------------------|-----------------------|--------------------------|
| Values                  | 12                    | 13                  | 6.5                       | 2.3                   | 2.3                   | 6                        |

Figure 7. The drawing of the turbine gas journal bearing.

3. The room temperature testing process and results

The processing, cleaning and assembly of the helium turbines has been completed. The room temperature testing has also been carried out. The start-up process is very stable, and the speed
fluctuation is very small and the repeatability is good. During the testing, the inlet pressure can be increased from 0.1 to 0.81 MPa (Absolute) within 5 seconds. The speed basically reaches the design value and can reach 247 krpm. Inlet temperature is about 305 K, and the outlet temperature is about 265 K; the temperature difference is more than 35 K. The vibration amplitude is less than 0.010 mm. Hence the mechanical performance meets design requirements. That is to say the gas bearings and the shafts meet the design requirements.

Figure 8. The picture of the helium turbine testing process.

Figure 9. The helium turbine outlet of the testing process.

4. Conclusions
The 500 W helium turbines have been designed, manufactured and room temperature tested. In balance testing the left unbalance quality is less than 1.0 mg at 8 krpm. The expander impeller, nozzle, diffuser and the brake impeller have been designed and manufactured. The room temperature testing results meet the rotor speed needs of about 247 krpm, and the vibration amplitude is less than 0.010 mm. The low temperature testing will be carried out in the future.

The turbines are important mechanical devices in the cryogenic plant of the 500 W / 4.5 K cryogenic system, which has very wide applicability. The detailed design methodologies for such turbines have been developed at Institute of Plasma Physics Chinese Academy of Sciences (IPPCAS). The design process and measurement results can be used for future studies on cryogenic turbines for helium refrigeration and liquefaction cycles.

5. References
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