Development of a cryogenic performance experiment system for centrifugal cold compressors

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Abstract. Cold compressors are key components in large scale superfluid helium refrigerators. A cryogenic performance experimental system for centrifugal cold compressors is under development; this mainly consists of a warm compressor station, cold compressors, valves, a cold box, a sub-cooling heat exchanger and a sub-atmospheric heater. The flow scheme has been specially designed so that cold compressors with a flow rate less than 30 g/s and inlet temperatures between 3 K and 20 K can be tested. An innovative sub-atmospheric heater has been designed to guarantee good heat transfer efficiency between the helium gas and the wall of the tube. The design and fabrication of the cold box and cold compressors have been completed. The commissioning of the system is foreseen in the near future.

1. Introduction

With recent developments in high-energy physics, tokamaks and particle accelerators the requirement for superfluid helium cryogenic systems in these big science facilities becomes more and more urgent. The cold compressor is one of the key devices in the large scale superfluid helium refrigerator. The high performance and stability of cold compressors over a wide range, during both steady and transient modes, are the biggest challenges. Developing a cryogenic performance experimental system is necessary to improve the adaption of cold compressors to these needs.

During recent years, experience has been accumulated gradually and the performance of cold compressors has been improved. Fermilab tested the cold compressors which were installed in the AI refrigerator and had both successful and unsuccessful experiences, such as the setup of the inlet filter, the control method of the heater and the parameters of the control loop [1]. CERN has built a dedicated cryogenic test station which connected to one 18 kW @ 4.5 K refrigerator to test the performance of the cold compressors produced by Air Liquide and IHI. The mean time between maintenance of the cold compressor cartridges and the subsequent recovery after the system trip was verified [2]. In this paper, we report on the cryogenic performance test station which has been designed to study the stability and thermal efficiency of independently developed cold compressors with active magnetic bearings and variable frequency during steady and transient modes. The experience and experiment results can provide guidelines for future design.
2. Flow scheme of cryogenic test system of cold compressor

The main function of the cryogenic test station is to provide the environment for testing the stability, reliability and performance of the cold compressors during different working conditions, defined by inlet temperature, inlet pressure, mass-flow rate and outlet pressure. The rated working parameters of the cold compressor station are given in Table 1.

Table 1. Rated design parameters of the cold compressor station.

| Name                  | Parameters               |
|-----------------------|--------------------------|
| Mass flow             | 28g/s                    |
| Inlet pressure        | 2.8 kPa ± 10%(abs)       |
| Inlet temperature     | 3.4K ± 10%              |
| Outlet pressure       | ≥42 kPa(abs)            |
| Isentropic efficiency | ≥65%                     |

The process flow diagram of the experimental system is shown in Figure 1. The experimental system includes the vacuum insulated cold box, the liquid helium tank, the liquid nitrogen tank, the sub-atmospheric heater, the vacuum pump, the warm screw compressor station, the control system and other auxiliary facilities. The cold box is composed of the 4.5 K liquid helium (LHe) tank, the subcooled helium tank, the sub-atmospheric heat exchanger, the 2 K superfluid helium tank with heater, three cold compressors and the cold shield of liquid nitrogen (LN2).

During the precooling process, the valve CV4 is opened and the liquid nitrogen is pumped from the LN2 tank to the pipes of the cold shield. The liquid nitrogen absorbs heat and is released as nitrogen gas to the atmosphere. The next step is to use helium gas for further precooling the facilities and purging the residual impurities. The valves CV2, CV5 and CV7 are opened, allowing the helium from the LHe tank to flow through the inner 4.5 K LHe tank, the 2 K superfluid helium tank, the sub-atmospheric heat exchanger and, finally, to the recovery system. The cooling rate can be improved by closing valve CV6 and opening valves CV1, CV2, CV5 and CV7 to precool the 4.5 K LHe tank, the subcooled helium tank and the 2 K superfluid helium tank quickly. When the above tanks store some liquid helium, CV6 is opened to decrease the temperature of the pipes and components downstream of it. The sub-atmospheric heater starts to work when the temperature of the helium gas is lower than the environment. Finally, the helium gas is compressed and returned to the recovery system by the vacuum pump and the warm screw compressor.
When the inlet pressure of the first stage cold compressor is reduced to about 20 kPa, the cold compressors start to work to pump-down the pressure of helium gas to 2.8 kPa. In order to satisfy the inlet pressure of vacuum pump, the speed of the cold compressors is controlled to maintain the pressure differential at a reasonable level. After the last compressor, the temperature of the helium gas is about 20 K while the pressure is about 42 kPa. The helium gas is heated to about 300 K by the sub-atmospheric heater, and compressed from 42 kPa to about 1 bar by the vacuum pump. The warm screw compressor raises the pressure of the helium gas from 1 bar to the design pressure of the recovery system. The mass flow rate of the cold compressor station can be adjusted by the heater in the 2 K superfluid helium tank and the bypass valve CV7. The inlet temperature of the cold compressor station can be controlled by the mass flow rate through CV6 and the power of the heater.

3. Main system compositions

3.1. Sub-atmospheric heat exchanger

Aluminum plate-fin heat exchangers have a compact structure, large effective heat transfer area and high efficiency. In the superfluid helium system, the plate-fin heat exchanger is adopted to obtain good performance. The design parameters of the hot and cold streams are shown in table 2. Owing to the above special working conditions, the balance between the pressure drop and the heat transfer performance of the cold stream has to be specially considered during the design stage. The lower pressure loss of the cold stream is beneficial in making the pressure requirements of the cold compressor less demanding. The laminar flow with low Reynolds number meets the demand of the lower pressure loss but the heat transfer is weakened. A better method is to optimize flow channel layout in the turbulent region and improve heat transfer effect as early as possible. Eventually, the pressure loss is limited to less than 300 Pa by design. Through heat exchanger simulation, we can obtain that the heat transfer performance meets the design demands. The outlet temperature of the hot and cold streams is 2.14 K and 3.48 K; the pressure drop of the cold stream is about 130 Pa.

| Name                  | Hot stream | Cold stream |
|-----------------------|------------|-------------|
| Mass flow             | 28 g/s     | 28 g/s      |
| Inlet pressure        | 1.25 bar(abs) | 0.31 bar(abs) |
| Inlet temperature     | 4.45 K     | 2 K         |
| Outlet temperature    | 2.2 K      | 3.43 K      |
| Pressure drop         | 1 kPa      | ≤0.3 kPa    |

3.2. Cold compressor station

Figure 2. 3D models of the wheel and volute.
The cold compressor station includes three independently developed centrifugal compressors in series, which are driven by sub-atmospheric motors and fitted with active magnetic bearings. The pressure and temperature of the inlet helium gas are about 2.8 kPa and 3.4 K. In the design stage, the heat insulation from the cold part to the warm part is one of the important issues. Therefore, the polyurethane foam insulation and suspension setting of the cold compressors are adopted to decrease the cold loss. In addition, an independent thermal sink of 77 K is arranged inside the polyurethane foam layer. In the warm part, the heat of the sub-atmospheric motor is removed by the cooling water produced by the water chilling unit. The pressure ratio of the three cold compressors is 3.5, 2.85 and 1.5, respectively. The cold compressors rotate at 31,200 rpm, 50,000 rpm, and 50,000 rpm, respectively. The 3D design of the cold compressors was made using NREC software, and the models of the wheel and volute are shown in figure 2. The performance of the cold compressors has been simulated in ANSYS software, and the simulation result of the equivalent stress of the last compressor is shown in figure 3. The highest stress is about 66.15 MPa, and this value is far less than the yield stress of the aluminium alloy. Therefore, the design parameters of the wheel can guarantee an adequate safety margin.

3.3. Subcooled helium tank

Atmospheric pressure liquid helium is stored in the subcooled helium tank which is made of SS316 stainless steel with a volume of 105 litres. A copper coil is arranged inside the tank to cool the liquid helium at higher pressure. The 3D view of the subcooled helium tank is shown in figure 4; it has a diameter of 412 mm and a height of 900 mm.

3.4. Cold box

The cold box is the high vacuum insulated vessel which is composed of flanges and a vertical shell. In order to decrease the heat transfer, various methods have been adopted. Firstly, the LN2 cold shield is

Figure 3. Equivalent stress of the wheel

Figure 4. 3D view of the subcooled helium tank.

Figure 5. 3D view of the cold box.
arranged inside the cold box to decrease the heat transfer between the cold mass and the cold box outer shell. Secondly, the components in the cold box, such as the cold compressors, the subcooled heat exchanger and the cryogenic pipes, are covered with multilayer reflecting insulation sheets. Thirdly, the vacuum degree of the cold box is maintained at better than $10^{-2}$ Pa so that heat conduction via residual gas can be ignored. The whole cold mass is suspended on the upper flange, which can be removed for repair or exchange. The 3D-design of the cold box is shown in figure 5. The vacuum vessel has a diameter of 2020 mm and a height of 3350 mm.

3.5. Sub-atmospheric heater

The pressure of the helium gas in the heater is about 42 kPa. The heat transfer between resistance wire and the gas is weakened because the heater works in sub-atmospheric conditions. It is necessary that the heater have low pressure drop loss, is highly stable and convenient to maintain. In order to reach a compromise for these requirements, the heater has been designed specially and adopts two stages. The first stage is used to heat the cold helium gas from 20 K to 160 K, and the second stage continues to heat the helium gas from 160 K to 300 K. A 2D model of the heater showing the flow direction of helium gas in the vacuum vessel is shown in figure 6. The two stages are installed in series and each one includes two kinds of copper plates (one flat and the other 'C' shaped) which are welded together to form the oblong channels. Each stage has six big channels and six small channels. The heated rods are welded to the plates which are arranged as shown in figure 7. An interlaced arrangement of the heated rods in the channels ensures the helium gas has an even temperature distribution when it flows out of the sub-atmospheric heater. The flow direction of helium gas is perpendicular to the paper in figure 7, and the two stages have the same construction. The height of the heater is about 1500 mm, and the total heat transfer area of the two stages is about 30 m².

![Figure 6. 2D view of the sub-atmospheric heater.](image-url)

![Figure 7. Top view of the sub-atmospheric heater.](image-url)

4. Future work

A cryogenic experimental system which is dedicated to the study of the performance of cold compressors has been designed. Owing to some special operating conditions, the structure of the main components has been specifically optimized. Some key facilities such as the cold compressors and the cold box have been constructed. Future work will be to integrate and test the entire cryogenic experimental system and to obtain experimental experience to guide future design and measurement.

References

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Acknowledgement
This work was supported by the fund of Key Laboratory of Cryogenics, TIPC, CAS [grant numbers CRYOQN201711].