Thermodynamic cycle design of a 700W@3K sub-cooled helium refrigerator test facility

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Abstract. In order to increase the magnetic field and temperature margin of superconducting magnets, a test facility for a 3K sub-cooled helium refrigerator was proposed to decrease the operation temperature from the saturated helium to the sub-cooled helium. The process flow of 3K sub-cooled helium refrigerator has been analysed, including the 4.5K refrigerator unit and 3K refrigerator unit. Two cold compressors arranged in series have been adapted to decompress pressure to achieved 3K sub-cooled helium. The thermodynamic cycle of the 3K sub-cooled helium refrigerator have been designed, which can provide 2.5kW@4.5K in 4.5K mode or 1.2KW@4.5K + 700W@3K in 3K mode. As the most important port, the design parameters and mechanical test at normal temperature test of cold compressors were shown.

1. Introduction
In general, large-scale superconducting magnets are cooled by the supercritical helium (SHe) which is obtained from the saturated helium at 4.5K. In order to increase the critical current density, critical magnetic field and stability margin of superconducting magnets, the operation condition of cryogenic system should be upgraded from the saturated helium to the sub-cooled helium [1].

The toroidal field (TF) coil is the most important system in Experimental Advanced superconducting Tokamak (EAST). Operating parameters of TF will affect the device ability directly [2]. However, due to the early technology of large scale sub-cooled helium system, the superconducting TF coils are only cooled by SHe and limit the stability for the higher plasma parameters. Therefore, a test facility for a 3K sub-cooled helium refrigerator was proposed to achieve the test platform for large superconducting magnets supported by Chinese Academy of Sciences.

In this paper, the process flow of this test facility for a 3K sub-cooled helium refrigerator has been designed and analyzed. Two cold compressors arranged in series have been adapted to decompress pressure from 1.2bar to 24kPa to achieved 3K sub-cooled helium. Thermodynamic parameters of the 3K sub-cooled helium refrigerator have been calculated, which can provide 2.5kW@4.5K in 4.5K mode or 1.2KW@4.5K + 700W@3K in 3K mode. This 3K helium test facility will also be benefit to develop the key technologies of large scale sub-cooler helium refrigerator.

2. Description of the 3K sub-cooled helium refrigerator test facility
The purpose of this project is to implement a 3K sub-cooled helium test facility for large scale superconducting magnets and achieve a research platform for the 3K sub-cooled helium refrigerator. The test facility is comprised of a refrigeration cold-box for 4.5K refrigerator and a distribution cold-box to provide supercritical helium by helium pump and sub-cooled helium by cold compressors.
2.1. Functional requirements of the 3K sub-cooled helium refrigerator test facility

According to the heat load of EAST device and the refrigeration capacity of EAST cryogenic system, the proposed helium refrigerator can provide the refrigeration capacity of 2.5kW in 4.5K refrigeration mode or 1.2kW/4.5K+700W/3K in 3K mode. The detailed requirements were listed as below:

i) Operated in refrigeration mode, liquefaction mode or the refrigeration/liquefaction mix mode.

ii) Providing the forced-flow cooling with supercritical helium at 5bar by the circulation pump.

iii) Providing the sub-cooled helium at 3K through two cold compressors arranged in series.

iv) Providing 80K helium gas interfaces to superconducting magnets, and multiply bypass streams to utilize the returned cold gas from superconducting magnets.

v) Providing the independent test interfaces for the circulation pump and cold compressor.

2.2. Process analysis of the 3K sub-cooled helium refrigerator

2.5kW/4.5K helium refrigerator was a large scale helium refrigeration plant. The Claude refrigeration cycle of two turbines in series with LN2 pre-cooling was chosen. Besides, the Joule-Thomson (JT) stream was expanded by turbine to improve the refrigeration capacity [3]. The simplified process flow diagram for the 3K sub-cooled helium refrigerator was presented in figure 1, including the refrigeration coldbox and the distribution coldbox.

![Figure 1. Simplified process flow diagram of a 3K sub-cooled helium refrigerator](image)

- **Refrigeration coldbox**
  
  High Pressure (HP) helium gas was pre-cooled to 80K in HX1 and HX2 by LN2 and low pressure (LP) helium gas in counter flow. With LN2 pre-cooling unit, superconducting magnet could be realized the 300K-80K cool-down process respectively through mixed gas between 300K and 80K helium gas.

  Then HP helium gas was split into two parts between HX3 and HX4: turbine stream and JT stream. Turbine stream was expanded in T1. After a further cooled down in HX5, turbine stream entered turbine T2 and was expanded to low pressure and finally joins into the returned JT stream.

  The JT stream was cooled down further in HX7 and expanded to 4bar by T3, and then entered to the final heat exchanger. JT stream provided SHe for superconducting magnets. The gas returned from superconducting magnets was re-entered to cold box and warmed up in HX8 and HX7 before joined into the turbine cycle gas.

  Then the LP stream was warmed in counter flow by the HP stream in heat exchangers and entered the suction line of the compressor. It also provided multiply bypass valves according to the retuned temperature in order to utilize the cooling power and shorten the cool-down time.

- **Distribution coldbox**
  
  It could provide SHe from JT stream with limited mass flow. It also could increase the mass flow of SHe through the helium circulation pump of P1 or P2.

  Liquid helium from LHe dewar was cooled down in sub-pressure heat exchange HX9 and joined to LHe vessel. The saturated helium at 1.2bar in liquid helium vessel was decompressed to sub-pressure at 24kPa to obtain 3K sub-cooled helium through two cold compressors arranged in series.
3. Thermodynamic cycle for the 3K sub-cooled helium refrigerator

The thermodynamic calculation of the refrigerator was optimized through the static simulation based on the different objective function with independent variables [3]. The design of thermodynamic cycle was consisted of the pressure cycle, temperature cycle and mass-flow cycle, considering the efficiency and the effectiveness of real components, such as compressor, turbine expander and heat exchangers [4].

3.1. Thermodynamic Calculation in 4.5K Refrigeration Mode

This test facility of 3K sub-cooled helium refrigerator will utilize the compressors of EAST cryogenic system. The pressure cycle design was based on the EAST compressors with two-stage compress [5]. The T-S diagram 2.5kW@4.5K in 4.5K refrigeration mode was shown in figure 2. The suction pressure of compressors was 1.05bar, the intermediate pressure was 5.1bar and discharge pressure was 21bar. After the cooling water and oil removal system, the inlet pressure to the cold box was 20bar. The mass-flow of compressors were 245g/s with turbine stream of 98g/s and JT stream of 147g/s. The consumption of LN2 was about 18.2g/s. The total UA values of heat exchanges were 6.74×10^4 W/C.

![Figure 2. T-S diagram in 4.5K refrigeration mode](image)

3.2. Thermodynamic Calculation in 3K Refrigeration Mode

The T-S diagram of 1.2kW@4.5K+700W@3K in 3K refrigeration mode was shown in figure 3. The pressure stages of the compressor station were the same with 4.5K mode. The mass-flow of compressors was 238g/s with turbine stream of 98g/s and JT stream of 140g/s. The consumption of LN2 was about 18.4 g/s. The total UA values of heat exchanges are 6.94×10^4 W/C except the HX9.

![Figure 3. T-S diagram in 3K sub-cooled mode](image)
4. Design parameters and mechanical test of cold compressors
In order to decrease the size of coldbox and increase the operation efficiency, the process flow was
designed based on two cold compressors instead of the vacuum pumps.

4.1. Design parameters of Cold compressors
The detailed design parameters were shown in table 1. These two cold compressors were manufactured
by ATEKO. The feed temperature of CC1 was warmed up to 3.727K through the sub-pressure heat
exchange HX9, which can reduce the technical requirements of cold compressor.

Table 1. Parameters of cold compressors.

| Parameter               | Units | CC1     | CC2     |
|-------------------------|-------|---------|---------|
| Helium flow rate        | g/s   | 32.8    | 32.8    |
| Inlet pressure          | kPa(a)| 16.4    | 44.40   |
| Inlet temperature       | K     | 3.727   | 6.441   |
| Outlet pressure         | kPa(a)| 44.4    | 120.00  |
| Compression ratio       | -     | 3.7     | 2.7     |
| Isoentropic efficiency  | %     | >=65    | >=65    |
| Rotor speed             | rpm   | 43000   | 43000   |

4.2. Mechanical test at room temperature
Limited by the schedule of the facility, it was impossibility to ensure normal operating conditions for
the cold compressors, such as the temperature, pressure and so on. Therefore, the mechanical performance
of these two cold compressors were tested with air instead of circulated medium, helium.

Two cold compressors were tested together and were vacuumed before start. The mechanical test
was executed at low pressure about 5 kPa(a) and temperature about 20°C. The test process and records
of the CC1 and CC2 were shown in figure 4.

![Figure 4. Records of mechanical running test for CC1,CC2](image)

CC1 and CC2 both were started and ran up to 20000 rpm quickly. Then the speed was step up to
rated speed of 43000 rpm in two minutes. After reaching to the set speed, CC1 and CC2 were operated
steadily on the rated speed for one hour. In addition, the reactions of CC1 and CC2 to the required speed
were done, and then CCs reached to the rated speed of 43000 rpm again. At last, automatic alarm
reactions were tested successfully, and both CCs were shut down.
5. Conclusions
The test facility of a 3K sub-cooled helium refrigerator has been designed including function requirements and process analysis. Thermodynamic cycle in 3K sub-cooled mode was calculated based on two cold compressors arranged in series. As the most important devices, design parameters of cold compressors were shown. The mechanical performances of two cold compressors at room temperature were tested including the start process, the response to the required speed and one hour running at rated speed. This facility will be beneficial to the sub-cooled test for large scale magnets, as well as to design and construct the large scale sub-cooled helium refrigerators.

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