Design and Commissioning of a 700 W@3 K Sub-cooled Helium 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 700 W@3 K sub-cooled helium refrigerator was proposed to decrease the operation temperature from 4.5 K down to 3 K. The process flow of the 3 K sub-cooled helium test facility has been designed with two cold compressors arranged in series to pump the vapour pressure from 120 kPa to 24 kPa. This 3 K sub-cooled unit has been constructed and operated successfully to decompress the 4.5 K saturated helium to 3 K sub-cooled helium. The preliminary commissioning results indicated that this 3K sub-cooled helium unit could achieve more than 700 W capacity at 3 K sub-cooled helium. Thermodynamic parameters and performances of this 3 K sub-cooled helium unit were introduced and compared with the designed values in good agreement. The rotation speeds, pressures and temperatures of cold compressors during the transient state and the steady state were also analysed.

1. Introduction
In general, large-scale superconducting magnets are cooled by the supercritical helium (SHe) which is obtained from the saturated helium at 4.5 K. 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].

Toroidal Field (TF) coils are the most important system in Experimental Advanced Superconducting Tokamak (EAST). The operating parameters of TF coils will affect the device ability directly [2]. However, lack of the technology of large scale sub-cooled helium system at an early stage, the TF superconducting coils are only cooled by SHe. Therefore, a test facility for a 3 K sub-cooled helium refrigerator was proposed to achieve the test platform for large superconducting magnets, which was supported by Chinese Academy of Sciences.

In this paper, the process flow of the test facility for a 3 K sub-cooled helium refrigerator has been described. In order to achieve 3K sub-cooled helium, two Cold Compressors (CCs) arranged in series have been adapted to pump the pressure from 120 kPa to 24 kPa. This 3K sub-cooled unit has been constructed and operated successfully to decompress the 4.5K saturated helium to the 3 K sub-cooled helium. The preliminary commissioning results indicated that this test facility could achieve more than 700 W@3 K sub-cooled helium. The start-up process and steady-state operations of this 3 K sub-cooled helium unit were introduced and analysed. This 3 K helium test facility will also be benefit to develop the key technologies and operations of the large scale sub-cooler helium refrigerators.
2. Description of the 3 K sub-cooled helium refrigerator test facility
The purposes of this project were to implement a 3 K sub-cooled helium test facility for large scale superconducting magnets and achieve a research platform for the sub-cooled helium refrigerator. The test facility was comprised of a 4.5 K refrigeration cold box and a 3 K sub-cooled distribution cold box to provide supercritical helium by helium pump and sub-cooled helium by cold compressors [3].

2.1. Functional requirements of the 3 K 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 could provide the refrigeration capacity of 2.5 kW in 4.5 K refrigeration mode or 1.2 kW@4.5 K+700 W@3 K in 3 K 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 5 bar by the circulation pump.

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

iv) Providing 80 K helium 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 3 K sub-cooled helium refrigerator
2.5 kW@4.5 K helium refrigerator was a large scale helium refrigeration plant. The Claude refrigeration cycle of two turbines in series with LN2 pre-cooling was chosen [4]. Besides, the Joule-Thomson (JT) stream was expanded by turbine T3 to improve the refrigeration capacity and efficiency [5]. The simplified process flow diagram for the 3 K sub-cooled helium refrigerator was presented in figure 1, including the 4.5 K refrigeration coldbox and the 3 K distribution coldbox.

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

2.2.1. Refrigeration cold box
High Pressure (HP) helium gas was pre-cooled to 80 K 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 300 K–80 K cool-down process respectively through mixed gas between 300 K and 80 K 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 400 kPa 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.

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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.

2.2.2. Distribution cold box
It could provide SHe from JT stream. It also could increase the mass flow of SHe through the helium circulation pump of P1 or P2. EX1 was designed to precool the superconducting coils. Heat loads produced by superconducting coils and circulation pump were taken off by EX2 and EX3.

Liquid helium from LHe Vessel_1 was cooled down in sub-pressure heat exchange HX9 and joined to LHe Vessel_2. The saturated helium at 120 kPa in liquid helium vessel was decompressed to sub-pressure at 24 kPa to obtain 3 K sub-cooled helium through two cold compressors arranged in series.

2.3. Design parameters 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 vacuum pumps. The updated design parameters were shown in table 1. Two cold compressors were manufactured by ATEKO. Feed temperature of CC1 was warmed up to 3.865 K in the HX9, which can reduce the technical requirements of cold compressor.

Table 1. Updated design parameters of cold compressors.

| Parameters                     | Units | CC1   | CC2   |
|--------------------------------|-------|-------|-------|
| Helium flow rate               | g/s   | 32.8  | 32.8  |
| Inlet pressure                 | kPa   | 18    | 65.00 |
| Inlet temperature              | K     | 3.865 | 7.5   |
| Outlet pressure                | kPa   | 69.3  | 130.00|
| Outlet temperature             | K     | 7.45  | 11.1  |
| Compression ratio              |       | 3.85  | 2     |
| Isentropic efficiency          | %     | ≥65   | ≥65   |
| Rotor speed                    | rpm   | 43000 | 43000 |

3. Commissioning of the 700 W@3 K sub-cooled helium unit
At present, this 3 K sub-cooled helium unit has been constructed without the 4.5 K refrigeration unit, which was still under construction. In order to test the 3 K sub-cooled unit, EAST helium refrigerator was used instead of the 4.5 K refrigeration unit, which can provide capacity about 2 kW@4.5 K [6].

3.1. Speeds and mass flow of CCs during the start-up process
Speed and mass flow curves of CCs under heat load during the start-up process were shown in figure 2.

Figure 2. Speed and mass flow curves of CCs during the start-up process
The speeds of CCs were increased step by step. At first stage, mass flows of CCs were increased immediately along with the speeds of CCs. Therefore, an electric heater in LHe Vessel_2 was used to simulator the heat load. During the start-up process, the power of the electric heater was increased along with the speeds in order to match the mass flow.

3.2. Pressures of CCs during the start-up process
The pressure curves of CCs during the start-up process were shown in figure 3. With the accumulation of mass flow, the pressures of LHe vessel and CC1-in were decreased obviously. The pressures of CC1-out and CC2-out were increased due to the compression by CC1 and CC2. After the speeds of CCs reached to the set-points, the pressures and the mass flow of CCs reached to the steady-state.

![Figure 3. Pressure curves of CCs during the start-up process](image)

3.3. Temperatures of CCs during the start-up process
The temperature curves of CCs during the start-up process were shown in figure 4. After CCs were started, inlet and outlet temperatures of CCs were dropped to 5–6 K quickly due to the cooling fluid from LHe vessel. With the increment of mass flow, outlet temperatures of CCs increased due to the heat load from CCs. After the pressure was drawn to the set-point, temperature of LHe vessel reach to 3 K.

![Figure 4. Temperatures of CCs during the start-up process](image)
3.4. Comparisons of CCs between design and experiment data in steady-state

After the speeds of CCs and heat load increasing to the set-points, 3 K sub-cooled unit reached to the steady-state. This 3 K sub-cooled unit was operated successfully to decrease the 4.5 K helium down to 3 K sub-cooled helium.

The comparison of the design parameters and experiment data of CCs were shown in figure 5. Temperatures and pressures of CCs were in good agreement. The sub-cooler heat exchange (HX9) was not used in the preliminary commissioning. So the inlet temperature of CC1 was lower than design data. The outlet pressure of CC2 was lower than design data, 110 kPa compared with 130 kPa. This also caused the mass flow was higher than design parameter, which was 34 g/s compared with 32.8 g/s.

![Figure 5. Comparisons of CCs between design and experiment data in steady-state](image)

4. Conclusions

A test facility of a 3 K sub-cooled helium refrigerator has been designed including function requirements and process flow based on two cold compressors arranged in series. This 3 K sub-cooled unit has been constructed and operated successfully. The preliminary commissioning results indicated that two cold compressors decompressed the pressure of LHe vessel to 22 kPa and achieve 3 K sub-cooled helium with more than 700 W@3 K capacity. The start-up process and steady-state of the 3 K sub-cooled helium unit were introduced and analysed with the experiment data, compared with the design parameters. This facility will be beneficial to the sub-cooled test for large scale magnets, as well as the operations of large scale sub-cooled helium refrigerators.

References
[1] Hamaguchi S, Imagawa S, Yanagi N, et al 2004 IEEE transactions on applied superconductivity, 14 1439-1442
[2] Shi Y, Wu Y, Liu B, et al 2014 Fusion Engineering and Design, 89 329-334
[3] Lu X F, Zhang Q Y, Zhou Z W et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 502
[4] Lu X F, Zhang Q Y, Qiu L L, et al 2017 IOP Conf. Ser.: Mater. Sci. Eng. 278
[5] Thomas R J, Ghosh P, Chowdhury K 2012 International Journal of Refrigeration 35 1188-1199
[6] Bai H, Bi Y, Zhu P, et al 2009 Fusion Engineering and Design 81 2597-2603

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