Control and Commissioning of a Subcooled Helium Cryogenic Testing Platform with Cold Compressors

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Abstract. The subcooled helium cryogenic testing platform with cold compressors has been operated successfully in the end of 2018 at the Institute of Plasma Physics, Chinese Academy of Sciences (CASIPP). It is the first subcooled helium cryogenic system based on the cryogenic decompression technique in China, which has been designed and constructed over two years by our own team. The subcooled helium cryogenic testing platform was designed to provide the 4.5 K supercritical helium for the helium forced-flow cooling with one helium circulating pump, and provide the 3 K subcooled helium with two cold compressors in series. It consists of one 2.5 kW@4.5 K helium refrigerator and one distribution valve box where the helium circulating pump and the cold compressors installed on it. This paper will present the process control flow of the distribution system and the design parameters of two cold compressors. During the commissioning, the startup and stop control flow of the two cold compressors have been determined. And their operation and control were performed within the safe operation area in the performance map. The testing result shows the lowest temperature and pressure of the saturated helium bath, and indicates the subcooled helium system has an equivalent refrigeration power greater than the design value of 700 W@3 K. The commissioning experience will help the reconstruction of the subcooled helium system for EAST Tokamak in future to enhance the cryogenic stability in higher magnetic field.

1. Introduction
The Experimental Advanced Superconducting Tokamak (EAST) has been successfully cooled down by 4.5 K supercritical helium (SHe) in fifteen experiments since 2006. Using subcooled helium as the coolant can reduce the coil temperature and improve the cryogenic stability of the superconducting coils, which will increase the magnetic fields and help to obtain higher plasma parameters in the fusion device [1]-[3]. As one of the critical sub-systems of EAST Tokamak, its cryogenic system can provide 3.5 K subcooled helium by a warm oil ring pump (ORP) at ambient temperatures pumping saturated liquid helium (LHe) of 4.5 K helium vessel in distribution valve box [4]. However, it is difficult to ensure long-time reliable operation of the subcooled helium system because of ORP’s poor mechanical and control performance. To improve the EAST subcooled helium system, a subcooled helium cryogenic testing platform with cold compressors has been designed and constructed to test the cold compression method for 3 K subcooled helium. The platform had a successful commissioning to
reach 3 K subcooled helium in the end of 2018 at CASIPP, and it is the first subcooled helium cryogenic system based on cryogenic pumping technique in China.

2. Description of subcooled helium system
The subcooled helium cryogenic testing platform is comprised of a 2.5 kW@4.5 K refrigerator and a cryogenic distribution system to provide SHe by helium circulating pump and subcooled helium by cold compressors. The helium refrigerator can provide the refrigeration capacity of 2.5 kW in 4.5 K mode or 1.2 kW@4.5 K+700 W@3 K in 3 K mode [5]. The simplified process flow of the refrigerator is similar to the EAST refrigerator, which can refer to the literatures [5] [6]. The cryogenic distribution system consists of a distribution valve box, a sub-atmosphere heat exchanger, a LHe vessel inside, and one helium circulating pump and two cold compressors in series as well as the cryogenic control valves on top of the valve box. Figure 1 is the supervisory interface of the subcooled helium distribution system on its control system, which shows its simplified process flow and instrumentation diagram.

The LHe from refrigerator flows through the sub-atmosphere heat exchanger HX9 and goes into the LHe vessel in the distribution valve box. There are three coiled-tube heat exchangers in the LHe vessel. Two centrifugal cold compressors with hybrid ceramic ball bearings are arranged in series to pump the saturated helium at 1.2 barA in LHe vessel to sub-pressure at 0.23 barA for 3 K subcooled helium. The gas helium (GHe) flows through HX9, the inlet valve and two cold compressors to low pressure of refrigerator. The design parameters of two cold compressors are listed in table 1. It is necessary to emphasize that measured data has to respect the situation of high speed turbo-machines which are calculated as total thermodynamic values of each points, not only the values measured as static.

The helium circulating pump is used to provide large mass flow of SHe for the forced-flow cooling of superconducting magnets. A detailed schematic flow sheet and main components design of the distribution system can be found in literature [7]. An electrical heater was used to simulate the heat load of the superconducting magnets because of no real magnets connected in this testing platform.

| Cold Compressors | CC1 | CC2 |
|------------------|-----|-----|
| Design Parameter |     |     |
| Helium mass flow rate (g/s) | 32.8 | 32.8 |
| Inlet total pressure (barA) | 0.179 | 0.65 |
| Outlet total pressure (barA) | 0.69 | 1.3 |
| Inlet total temperature (K) | 3.865 | 7.5 |
| Outlet total temperature (K) | 7.446 | 11.1 |
| Compression ratio | 3.85 | 2 |
| Isothermal efficiency (%) | >= 65 | >= 65 |
| Rotor Speed (rpm) | 43000 | 43000 |
| Wheel diameter (mm) | 66 | 66 |

3. Control and operation of subcooled helium system with cold compressors
In the subcooled helium system, the helium mass flow rate of the cold compressors was regulated by the electrical heater in the saturated bath and the bypass valve as the rotation speed of CCs changed. The amount of the vaporized helium from the saturated helium bath varied in proportion to the heater. To obtain 3 K subcooled helium, the electrical heater with rated power of 1000 W was used to immerse in the 2000 L LHe vessel, and regulate the power to control the mass flow rate of cold compressors.
Figure 1. Supervisory interface of subcooled helium distribution system on its control system.
The control system of the subcooled helium cryogenic testing platform was designed and implemented on SIMATIC S7-300 PLC system. Two cold compressors are controlled by SIMATIC S7-1200 PLC on site, which communicates with higher control system by Profibus DP. The cold compressors (CCs) driven by high speed motor situated in ceramic ball bearings with permanent volume of lubricating grease, are cooled by separated water circuit and controlled by 2 pieces of one-phase variable-frequency drive (VFD). The bearings are usually changed after a maximum of 2000 hours of operation time. The bearing vibration is checked with vibration sensors for monitoring the bearing’s mechanical status. Figure 2 shows the detailed measuring and control loops of two cold compressors in the supervisory interface. It has a main flow with an inlet valve and a bypass flow with a bypass valve for adjustment of the helium mass flow of the cold compressor and pre-cooling operation.

![Figure 2. Measuring and control loops of two cold compressors in the supervisory interface.](image)

The CCs are operated with the same helium flow rate but with different pressures and different temperatures. The motor of CC is checked by temperature sensor situated in winding. The cooling liquid will be circulated with temperature 25 degC (+/- 2 degC) which is required by the motor. The PLC-CC controls two CC machines during all operating regimes. It checks actual speed, supplying current and vibration of CCs and compares them with their limits. The operating point position of two cold compressors in the performance map which gives an estimated safety area will be controlled by modifying the CC speeds and all other secure parameters.

### 3.1. Start process of CCs

The cold compressors will be started after the whole cryogenic system is already precooled to the temperature about 4.2 K, that is the temperature of LHe boiling under atmospheric pressure. The inlet valve and bypass valve are opened in precooling period and CCs are without the power supply. The CCs can be freely turned by flowing He during the whole precooling period. Before the start, the control mode should be selected. There are eight types of control modes with different control parameter for CCs, which are speed, flow, inlet and outlet pressures, and three pressure ratios. During the start process, the CCs accelerate the speed and the control parameter will be controlled in its set point by VFD which directly influences the rotation speed. The bypass valve will be opened for approximate 15 % or controlled during this period in the sense of all CCs operating data, and will be closed when the inlet temperature fall under 3.8 K and controlled by the helium mass flow and...
pressure of saturated helium bath. Finally, the CCs are operating near the design parameters. The start control flow was summarized in figure 3.

![Control Flow Diagram](image)

**Figure 3.** Start control flow of two cold compressors.

### 3.2. Emergency operation and stop process of CCs

In the case that CC has some problem, such as exceeding of any limits, break down or other, once any alarm occurs, the PLC-CC control algorithm will reduce actual CC speed automatically step by step till the moment when the whole cryogenic system finish all secure operations. If the problem exits on one CC only, the PLC-CC will reduce the speed of this machine only. The other CC will operate without changes. Five alarm categories according to their seriousness were defined, and each has its own priority. The speed of CC will be reduced with different steps according to different alarm category. For instance, the reducing of speed due to vibration, current alarm will be -1000 rpm/sec, and due to temperature alarm will be -250 rpm/sec, and so on.

The CCs will be stopped when its PLC receives the stop command. The power of all CC machines is disconnected and the CCs are freely run out during stopping. The inlet valve and bypass valve are fully opened in the stop process.

### 4. Commissioning Results of subcooled helium system with cold compressors

Figure 4 shows the curves of the temperature and pressure in the saturated helium bath as well as the input power of the electrical heater during the operation of cold compressors. In the start of operation of the cold compressors, the control mode speed was selected and the rotation speeds started with a low speed of 11000 rpm, and then increased up to 20000 rpm, 30000 rpm until to the nominal speed
43000 rpm. With the increase of the CCs’ speed, the power of the electrical heater was also increased step by step to simulate the heat load and regulate the mass flow rate. The temperature and pressure of the saturated helium bath both dropped from the precooling point (4.28 K, 1.06 barA) to the values of subcooled helium (3 K, 0.22 barA), then remained constant. The whole decompression process took about 35 min. The power of the electrical arrived at 805 W, which equals the real equivalent cooling capacity of the subcooled helium system, greater than the design refrigeration power of 700 W.

Figure 4. Curves of the temperature and pressure in the saturated helium bath as well as the heater power during the operation of cold compressors.

The final measuring parameters entering in steady state of two CCs can be found in the figure 4. The Table 2 shows the calculated total values according to the measuring static values. During this commissioning, the actual operation parameters were found similar as the design parameters.

**Table 2. Operation parameters of two cold compressors in steady state**

| Cold Compressors | Operation Parameter | CC1   | CC2   |
|------------------|---------------------|-------|-------|
| CC1              | Inlet total pressure (barA) | 0.18  | 0.67  |
|                 | Outlet total pressure (barA) | 0.67  | 1.08  |
|                 | Inlet total temperature (K) | 3.12  | 7.26  |
|                 | Outlet total temperature (K) | 7.26  | 11.34 |
|                 | Pressure Ratio (PR) | 3.623 | 1.606 |
|                 | Corrected Mass Flow CMF (g/s) | 28.79 | 31.44 |

Figure 5 and Figure 6 present the performance maps with estimate safety area of two cold compressors. It is important to operate the cold compressors stably and safely to avoid entering the surge region.
which would cause damage to the equipment. The current operating point of each cold compressor has been drawn in each performance map according to the pressure ratio (PR) and corrected mass flow (CMF) in table 2. We can found that both actual operating points in the cryogenic commissioning were in safety area and far away from the surge line.

Figure 5. Actual operating point in performance map of CC1.

Figure 6. Actual operating point in performance map of CC2.
5. Conclusion
In this work, the subcooled helium cryogenic testing platform with cold compressors has been constructed and operated to obtain 3 K subcooled helium for the cooling of superconducting magnets. The commissioning results show that the subcooled helium system has a greater refrigeration capacity than the design value, which achieve the expected target. The using the cryogenic decomposition technique with cold compressors to obtain 3 K subcooled helium can reduce the vacuum requirement of low pressure loop of the whole cryogenic system. The start and stop control flow as well as the emergency operation of two cold compressors have been summarized in PLC control programs. The performance maps with estimate safety area of two CCs were investigated, on which the actual operation parameters were in safe area and close to the design values. The control and commissioning experience of the subcooled helium testing platform and cold compressors can provide guidance to the future upgrading of EAST subcooled helium system.

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