Present status and one upgrading method with a cold compressor of the EAST sub-cooling helium cryogenic system

Zhigang ZHU (朱志刚)1,2, Qiyong ZHANG (张启勇)1, Yuntao SONG (宋云涛)1, Ming ZHUANG (庄明)1, Zhiwei ZHOU (周芷伟)1, Anyi CHENG (成安义)1 and Ping ZHU (朱平)1

1 Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, People’s Republic of China
2 University of Science and Technology of China, Hefei 230026, People’s Republic of China

E-mail: zzw@ipp.ac.cn

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Abstract
Since 2006, the superconducting toroidal field (TF) coils of the Experimental Advanced Superconducting Tokomak (EAST) have been successfully cooled by supercritical helium at a temperature of 4.5 K and a pressure of 4 bara in eleven experiments. To obtain higher operating currents and magnetic fields it is necessary to lower the operating temperature of the TF coils. The EAST sub-cooling helium cryogenic system, with a warm oil ring pump (ORP), was tested twice in cool-down experiments, which made the TF coils operate at 3.8 K. However, the long term operational stability of the sub-cooling system cannot be guaranteed because of the ORP’s poor mechanical and control performance. In this paper, the present status of the EAST sub-cooling helium cryogenic system is described, and then several cooling methods below 4.2 K and their merits are presented and analyzed. Finally, an upgrading method with a cold compressor for an EAST sub-cooling helium cryogenic system is proposed. The new process flow and thermodynamic calculation of the sub-cooling helium system, and the main parameters of the cold compressor, are also presented in detail. This work will provide a reference for the future upgrading of the sub-cooling helium system for higher operation parameters of the EAST device.

Keywords: EAST, cryogenic system, helium refrigerator, sub-cooling helium, cold compressor

(Some figures may appear in colour only in the online journal)

1. Introduction
The superconducting toroidal field (TF) coils of the Experimental Advanced Superconducting Tokomak (EAST) have been successfully cooled by supercritical helium (SHe) to 4.5 K and 4 bara in eleven experiments since 2006. Lower operating temperatures allow the coils to carry higher current without quench, and consequently bring an increase in the magnetic fields, which help to obtain higher plasma parameters in the device [1]. As one of the critical sub-systems of the EAST, the EAST helium cryogenic system has the ability to provide 3.5 K refrigeration capacity by warm oil ring pump (ORP), as well as 4.4 K refrigeration capacity [2]. However, the helium refrigerator is usually operated in the 4.4 K refrigeration mode [3] and long term reliable operation of the sub-cooling helium cryogenic system cannot be guaranteed because of the ORP’s mechanical and control performance.

With the development of cryogenic technology and the requirement of higher magnetic fields, a large number of cryogenic systems below 4.2 K are utilized in tokomaks, particle accelerators, colliders, etc [4–9]. As shown in table 1, it is a trend to adopt cold compressors, based on cold compression or mixed compression, to obtain sub-cooling or superfluid helium in the cryogenic systems below 4.2 K. In order to improve the reliability and stability of the EAST sub-cooling helium cryogenic system in the future, this research explores an upgrading...
method. By summarizing its present status and analyzing several mature cooling methods below 4.2 K across the world, an upgrading method with a cold compressor is proposed. This work will provide a reference for the future upgrading of the sub-cooling helium cryogenic system to obtain higher operation parameters of the EAST device.

2. Present status of the EAST sub-cooling helium cryogenic system

Designed at a capacity of 1050 W/3.5 K + 200 W/4.5 K + 13 g s⁻¹ LHe + 13 kW/80 K [2], the EAST helium refrigerator comprised of the compressor station, cold box, valve box, LHe Dewar and so on [10] has an equivalent refrigeration capacity of about 2.8 kW/4.4 K (not including 13 kW/80 K for the cooling thermal shield). As shown in figure 1 (red solid line), the EAST sub-cooling helium cryogenic system, based on warm compression with cold recovery, consists of 4.4 K liquid helium tank, 3.5 K sub-cooling helium tank, counter-flow plate-fin heat exchangers, J-T valve, ORP, pipes and valves. Before expansion, the 4.4 K saturated liquid helium is pre-cooled by the returning sub-atmospheric pressure helium vapor to about 3.83 K in the heat exchanger EX13, which can notably improve the efficiency of J-T expansion. According to the study [11], the 3.5 K cooling capacity per unit can be maximally increased by 15.43% and 1.8 K cooling capacity per unit can be maximally increased by 63.38% when liquid helium is fully pre-cooled. Cold energy of the sub-atmospheric pressure helium vapor is recovered for pre-cooling of the incoming high pressure helium gas through an array of counter-flow plate-fin heat exchangers EX7-EX1 inside the cold box. The 0.37 bara and 300 K helium gas is compressed by ORP to 1.05 bara, and then enters the suction of the LP screw compressors to complete one cycle.

The EAST ORP, shown in figure 2, was converted from the SKA303 series liquid ring pump, in particular shaft sealing to decrease the risk of air in-leaks. Employing the same lubricating oil as screw compressors, it is also equipped with an oil separator and oil cooler. A check valve is installed in the inlet pipe of the ORP to prevent the oil returning to the sub-atmospheric pressure pipe and equipment when the ORP is shut down. The main parameters of the ORP are summarized in table 2.

In 2012, the EAST cryogenic system successfully operated at 3.5 K refrigeration mode. Figure 3 indicates the saturation pressure and temperature of the sub-cooling helium tank. It took only about one hour to cool down from 4.4 K to 3.5 K. After nearly 16 h operation, the coupling between the driven wheel and the shaft unfortunately came loose resulting in Figure 1. The simplified process flow of the EAST cryogenic system. In the figure, ‘EX’ means heat exchanger, ‘LN2’ means liquid nitrogen, ‘LHe’ means liquid helium, ‘THS’ means thermal shield, ‘HTS CL’ means high temperature superconducting current leads, ‘PF coils’ means poloidal field coils, ‘HP’ means high pressure, ‘LP’ means low pressure, ‘SUB-P’ means sub-atmospheric pressure.
in a failed connection. The temperature of the sub-cooling helium tank went on decreasing to 3.5 K after a repair of the coupling. The whole sub-cooling operation lasted about three days.

Before entering the ORP, the cold sub-atmospheric helium is heated to room temperature by an array of counter-flow plate-fin heat exchangers. The sub-atmospheric passages of large-sized heat exchangers and pipes work below atmosphere. Thus it is easy for air to in-take and contaminate the entire helium system, which greatly lowers the operation stability of sub-cooling helium cryogenic system. Moreover, the cooling capacity of the sub-cooling helium cryogenic system depends on the flow rate of the ORP. Once the heat load of sub-cooling helium cryogenic system varies, the flow rate adjustment of the ORP will be hysteretic [12]. Therefore, it is necessary to upgrade the EAST sub-cooling helium cryogenic system.

3. Cooling methods analysis below 4.2 K

It is generally known that the saturation temperature of helium at 1 atm is 4.2 K. All refrigeration systems below 4.2 K must perform compression to bring the sub-atmospheric vapor back to atmospheric pressure [13]. Figure 4 shows the compression ratio at different temperatures below 4.2 K. For 3.5 K a compression ratio of 2.15 is required, while for 1.8 K it exceeds 60.

Four types of cycle, shown in figure 5, are generally considered to produce refrigeration power below 4.2 K. Type A is warm compression without cold recovery, based on room temperature sub-atmospheric compressors. The cold helium vapor is heated to room temperature by an external heater, which is uneconomical and inappropriate for large-scale systems. Type B is warm compression with cold recovery by counter-flow heat exchangers in a cold box. It results in large volume flow rates for sub-atmospheric helium because of low density. As a result, large-sized warm compressors as well as sub-atmosphere counter-flow heat exchangers are required, which increase the size of the cold box and the costs of the whole cryogenic system. Moreover, it is easy for air to in-leak and contaminate the entire helium system. Type C is cold compression, based on cold compressors. Because of low suction temperature, the motor power consumed by the cold compressor is fairly small. Thus cold compression is usually adopted by large-scale superfluid or sub-cooling helium refrigeration systems. Type D based on a combination of warm compression and cold compression, is mixed compression. Such a cycle can accommodate a much larger

Table 2. Parameters of the EAST ORP.

<table>
<thead>
<tr>
<th>Item</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suction pressure</td>
<td>0.37 bara</td>
</tr>
<tr>
<td>Suction temperature</td>
<td>300 K</td>
</tr>
<tr>
<td>Discharge pressure</td>
<td>1.05 bara</td>
</tr>
<tr>
<td>Pressure ratio</td>
<td>2.84</td>
</tr>
<tr>
<td>Flow rate</td>
<td>3000 m³ h⁻¹</td>
</tr>
<tr>
<td>Power consumption</td>
<td>90 kW</td>
</tr>
</tbody>
</table>

Figure 2. EAST oil ring pump.

Figure 3. Pressure and temperature of the sub-cooling helium tank.

Figure 4. Compression ratio at different temperatures below 4.2 K.
dynamic heat load range [13–15]. Several typical refrigeration systems below 4.2 K are as follows.

### 3.1. MG 300 W/1.8 K helium refrigerator

The helium refrigerator with a refrigeration capacity of 300 W at 1.8 K, made by the Messer Griesheim Company in 1972 for the Nuclear Research Centre, Karlsruhe, Germany, is one of the oldest 1.8 K superfluid helium systems. As shown in figure 6, the refrigerator employs the Claude process with liquid nitrogen pre-cooling. To maintain an absolute pressure below 1600 Pa, about 16.4 g s\(^{-1}\) helium vapors are drawn off by four stage roots compressors and one stage reciprocating compressor at room temperature. The MG 300 W/1.8 K helium refrigerator has two huge cold boxes, one is for the 300 K–80 K stage with a size of 4.425 \(\times\) 2.1 \(\times\) 4.05 m, another is for the 80 K–1.8 K stage, with 3.4 m diameter and 4.5 m height [4].

### 3.2. LHD sub-cooling helium system

In order to generate higher magnetic fields for improving the performance of LHD plasma experiments, an upgrade of the cryogenic system was carried out in 2006 and now it is able to supply with sub-cooling helium at 3.2 K for coils. As shown in figure 7, the 3 K sub-cooling cryostat pressure is reduced from 120 kPa to 23 kPa by the two cold compressors in series connection. The mass flow rate of the cold compressor is 15.9 g s\(^{-1}\) and the rated rotation speed is 90 000 rpm. Detailed specifications of LHD cold compressors are shown in table 3. With an excellent cold compressor control system, the LHD upgraded sub-cooling helium system has achieved reliable operations over 6000 h for three years [9].

### 3.3. LHC 1.8 K refrigeration unit

The high field superconducting magnets in the LHC, totaling a cold mass of 36 000 t, operated at 1.9 K cooled by eight refrigeration units with 19.2 kW capacity at 1.8 K. A generic scheme of the 1.8 K refrigeration unit for the LHC is shown in figure 8. Because of different vendors, the 1.8 K refrigeration process cycles are based on a combination of three or four cold compressors in series with one warm sub-
atmospheric screw compressor. Those cold compressors use all active magnetic bearings and variable-frequency drives. The combinations of cold and warm compressors help the system to operate over a large range of steady-state and transient heat loads. Since early operation for physics in November 2009 the equivalent availability of each unit has been above 99% [7, 16].

With the maturity of cold compressor technology, the reliability and stability of those sub-cooling or superfluid helium systems have been significantly improved. There is a trend for more and more sub-cooling or superfluid helium systems to adopt cold compressors for large-scale scientific installations.

4. Upgrading method of the EAST sub-cooling helium cryogenic system

With the aim of improving stability and increasing availability of the EAST sub-cooling helium cryogenic system, a centrifugal cold compressor is therefore proposed to replace the ORP. A new simplified process flow of the EAST sub-cooling helium cryogenic system is shown in figure 9. The sub-atmospheric helium vapor is heated to 3.89 K by liquid helium in a counter-flow heat exchanger EX13, and then compressed to 1.2 bara by cold compressor. At the outlet of the cold compressor, the cold helium joins the low pressure pipe between EX6 and EX7 and is heated to room temperature in EX6-EX1. Because of no sub-atmospheric helium in EX1-EX7 after upgrading, the passage-ways of LP and Sub-P can be combined into one passage to make full use of the existing heat transfer area. At the same time, it will decrease the amount of sub-atmospheric equipment and the risk of air in-leaks.

For the cold compressor, the power consumed is

\[ Q_{cc} = \frac{k}{k-1} m_{cc} R g \left[ \left( \frac{P_6}{P_5} \right)^{\frac{k-1}{k}} - 1 \right] / \eta_{cc} \]  

(1)

where \( Q_{cc} \) is the power consumed by the cold compressor, \( m_{cc} \) is the mass flow of the cold compressor, \( T_5 \) and \( P_5 \) are, respectively, the inlet temperature and pressure of the cold compressor, \( P_6 \) is the outlet pressure of the cold compressor, \( R_g \) is the helium gas constant, \( k \) is the isentropic exponent and \( \eta_{cc} \) is the adiabatic efficiency of the cold compressor.

The reference parameters of the cold compressor are shown in table 4. It will be powered by high speed electro-motor situated in ceramic ball bearings lubricated by permanent volume of the grease. Those bearings are designed corresponding operation 8000–12 000 h without any maintenance and the stator of the electro-motor is cooled by closed water circuit.
The power consumed by the cold compressor is just about 623 W while ORP is 90 kW. In this view, it is energy saving to replace ORP with cold compressor.

According to the latest experimental data of the cold end stage, the refrigeration capacity of the EAST cryogenic system is about 2.43 kW at 4.4 K, which is lower than the designed value. Thus, the present cryogenic system is enough for EAST cryogenic users [17]. Because it usually operates in 4.4 K refrigeration mode, the passageways of LP and Sub-P of EX6-EX7 are combined into one passage for simplifying the calculation, as shown in figure 10. Supposing the inlet temperature of the HP stream of the cold end stage (or EX6) after upgrading is the same, the outlet temperature of the EX6 LP stream is just 0.17 K higher than present after thermodynamic calculation of the cold end stage. This error can be ignored. The EAST upgraded helium refrigerator with cold compressor will have refrigeration capacity of 1086 W/3.5 K + 790 W/4.4 K, an equivalent refrigeration capacity of 2160 W/44 K. It is the heat load of the cold compressor that leads to the imbalance flow of EX7 and causes an equivalent refrigeration capacity degradation. However, the EAST helium refrigerator still has a margin in refrigeration capacity. Accordingly, the upgraded EAST cryogenic system still can meet the cooling requirements of all cryogenic users.

5. Conclusions

Lowering the operating temperature of the EAST TF coils is a good way to obtain higher magnetic fields and plasma parameters operation in future. Based on its present status and the latest development of the cooling methods below 4.2 K, one upgrading method with the cold compressor is presented in this paper for the EAST 3.5 K sub-cooling helium cryogenic system. The new flow process of the sub-cooling helium system and the main parameters of the cold compressor are also presented. Though the cold compressor causes the equivalent refrigeration capacity degradation, the upgraded EAST cryogenic system still can meet the needs of cryogenic users. Above all, this upgrading method with a reliable cold compressor can decrease consumed power and the amount of sub-atmospheric equipment, which contribute to high stability.

Table 4. Parameters of cold compressor for the EAST sub-cooling helium system.

<table>
<thead>
<tr>
<th>Items</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Centrifugal</td>
</tr>
<tr>
<td>Bearing</td>
<td>Ceramic ball</td>
</tr>
<tr>
<td>Suction pressure</td>
<td>0.46 bara</td>
</tr>
<tr>
<td>Suction temperature</td>
<td>3.88 K</td>
</tr>
<tr>
<td>Discharge pressure</td>
<td>1.2 bara</td>
</tr>
<tr>
<td>Pressure ratio</td>
<td>2.61</td>
</tr>
<tr>
<td>Mass flow rate</td>
<td>50 g s⁻¹</td>
</tr>
<tr>
<td>Adiabatic efficiency</td>
<td>65%</td>
</tr>
<tr>
<td>Discharge temperature</td>
<td>6.47 K</td>
</tr>
<tr>
<td>Power consumption</td>
<td>623 W</td>
</tr>
</tbody>
</table>
and reliability of the EAST sub-cooling helium cryogenic system.

**Acknowledgments**

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