Design of 2kW/4K Helium Refrigerator for HT-7U

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The HT-7U superconducting tokamak is an advanced steady-state plasma physics experimental device to be built at the Institute of Plasma Physics, the Chinese Academy Sciences (CASIPP). All of the toroidal field (TF) magnets and poloidal field (PF) magnets are made of NbTi/Cu CICC and are cooled with forced flow supercritical helium at 3.8 K. A refrigerator with an equivalent capacity of 2 kW/4K will be built to fulfill the requirements of all the operational modes, such as cool-down, warm-up, normal operation with current and quench of superconducting magnets. The helium refrigerator is designed in CASIPP and the thermodynamic analysis results and design of the refrigerator are presented in this paper.

INTRODUCTION

The HT-7U is a fully superconducting tokamak to be built at the Institute of Plasma Physics, the Chinese Academy Sciences (CASIPP)[1]. The project is to study the physical and technical issues involved in steady state tokamak nuclear fusion devices.

The HT-7U consists of 16 superconducting toroidal field (TF) coils and 14 superconducting poloidal field (PF) coils[2]. All of the coils are made of NbTi/Cu Cable in Conduit Conductor (CICC) and will operate at 3.8 K with supercritical helium (SHe)[3]. All of the TF coils are electrically connected in series and the nominal operating current is 14.3 kA, which produces a toroidal magnetic field of 3.5 T at a plasma radius of 1.7 m and 5.8 T peak field on the TF coils. The maximum current of PF coils is 14.5 kA and has a peak field of 4.5 T on the central solenoid coils. The magnets have a total cold mass of about 170 tons, including 96 tons for the TF coils, 38 tons for the intercoil structure and 35 tons for the PF coils.

The magnets have to be connected to power supplies at room temperature through superconducting buslines and current leads. 16 TF coils have one pair of current leads and the PF coils have six pairs of current leads. All of the current leads are about 12 m away from the tokamak and are cooled by the liquid helium at the cold end of the current leads. The superconducting buslines are also made of CICC and are cooled by forced flow SHe.

Thermal shields facing the vacuum vessel and the cryostat will be installed to reduce the heat loads on the superconducting magnets. They have a total mass of 20 tons and are cooled by 5.2 bar helium at inlet temperature of 57 K.

All of the cold components in the tokamak system will be refrigerated by a helium refrigerator, which is sized according to the total heat loads estimation on the cold components. The heat loads of the magnets consist of heat radiation, residual gas conduction, all kinds of heat conduction, Joule heating, ac losses, nuclear heating and heat loss from the SHe pump. Heat loads also include the losses in the helium transfer lines and CICC buslines, and the heat loss of the valves and instrumentation inserts. According to the estimation of the heat loads, the helium refrigerator is designed at a capacity of 1050 W/3.5 K + 200 W/4.5 K + 13 g/s LHe + 13 kW/80 K. It is approximately equivalent to a 2 kW helium refrigerator at 4 K.

HELIUM REFRIGERATOR

The helium refrigerator will be flexible to fulfill all the operational modes of HT-7U, such as cool-down, warm-up, standby and normal operation modes with current in the superconducting coils. The refrigerator
will be able to run in the liquefaction mode as well. The design also ensures the emergency operations such as quench of TF or PF magnets.

The refrigeration system is composed of compressors, an oil removal system, dryers, a coldbox, a valve box, a liquid helium dewar, helium storage and supply system, purification units and so on.

**Refrigeration process**

The helium refrigeration system has two refrigeration cycles. The refrigeration power and the liquefaction at 3.5 K and 4.5 K are produced by the primary refrigeration cycle. The refrigeration at 80 K is produced by another refrigeration cycle. Figure 1 shows a schematic flow sheet of the refrigeration system.

Liquid nitrogen is employed to pre-cool helium to 80 K. To get the full refrigeration power, almost 10 m³/day of liquid nitrogen is to be purchased from companies.

In the primary refrigeration cycle, turbine T1 and T2 are arranged in series. They have a mass flow rate of 100 g/s. At the J-T cooling stage, 110 g/s helium expands through turbine T3 from 20 bar to 4.5 bar. The helium is then liquefied by the Joule-Thomson effect in the liquefaction mode or is supplied to cool the superconducting magnets. The temperature - entropy diagram is shown on figure 2. The exergy flow diagram is shown on figure 3. If the total efficiency of compressors is the 50%, then the exergy efficiency of the refrigerator attains 21.8%.

The refrigeration temperature of 3.5 K requires to reduce the pressure of the subcooler to 0.47 bar. The sub-atmospheric pressure will be obtained by an oil ring pump, which can reduce the suction pressure to 0.37 bar at the volumetric flow rate of 3000 m³/h and give a refrigeration of 1050 W/3.5 K.

The refrigerator usually operates at mixed mode with liquefaction and refrigeration. The current leads will be cooled by the liquefaction.

The refrigeration cycle of 80 K has a turbine T4, through which 19 bar helium expands down to 5.3 bar to get a refrigeration power of about 13 kW/80K. This refrigeration is for the cooling of the 80 K thermal shield, compensates the basic heat loads of the thermal shield from the cryostat and the plasma chamber. While the plasma chamber operates in baking modes, the wall temperature would change from room temperature to more than 100°C, resulting in higher heat loads on the thermal shield. The loop allows the cooling capacity for the thermal shield to be increased to 25 kW/90 K or even more by liquid nitrogen. The temperature-entropy diagram of the cycle is shown on figure 4, where the refrigeration power is enhanced by liquid nitrogen to 25 kW/90K.

**Compressor station**

Screw compressors are used to supply compressed helium to the coldbox. There are five oil injected screw compressors arranged in two stages, with a low pressure stage of three screw compressors and a high pressure stage of two screw compressors.

The three low pressure stage compressors run with a suction pressure of 1.04 bar and an exhaust
pressure of 5.1 bar. Each compressor has a mass flow rate of more than 80 g/s and a 200 kW motor. Two high pressure stage compressors run with suction pressure of 5.1 bar and exhaust pressure of 20 bar. Each compressor has a mass flow rate of more than 80 g/s and a 355 kW motor.

To store the required pure helium for the running of the refrigerator and the cooling of the cold mass, two He buffers of 100 m³ (19 bar) each are used. They can be switched to supply and recover helium between the suction side of the low pressure stage compressors and the discharge side of the high pressure stage compressors. Four control valves are used to control the low pressure, the middle pressure and high pressure of the system.

**Oil removal system**

Downstream of the compressors, the oil is removed by a four-stage oil removal system: a fine oil filter, two coalescers of super-fine glass fiber, and finally an oil adsorber of active charcoal. The oil removal system reduces the oil-residuals down to 0.01 ppm(w).

The oil removal system is followed by a silicon gel/molecular sieve dryer to remove water vapor in the helium flow.

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**Coldbox**

All of the heat exchangers, turbines, 80 K and 20 K adsorbers, four turbines, are installed in a vacuum insulated vessel—coldbox. The coldbox is cylindrical, vertical installed and de-mountable type which makes the maintenance feasible in the coldbox.

Heat exchangers (Ex1~Ex8) are of the aluminum plate-fin type. All the heat exchangers with a total weight of about 2 tons will be manufactured in Kaifeng Air Separation Group Co., Ltd.

The primary refrigeration loop and the 80 K refrigeration cycle each have one pair of active charcoal
adsorbers in the coldbox in order to further remove impurities, such as nitrogen and oxygen.

Four turbines are supplied by Geliymash (Russia). The turbine module is a centripetal turbine with impeller of radial-axis type. The rotor is rotating in combined gas-oil bearings. The radial bearing on the impeller side is a gas-static one, the radial bearing on the side of the brake is an oil bearing. Axial thrusts to the rotor are taken by hydrostatic thrust bearings. On the shaft end on the side of the impeller there is a labyrinth seal with rotating crests that decrease the leakage along the shaft. Table 1 shows the specification of the turbines.

Table 1. Turbine specification

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Turbine 1</th>
<th>Turbine 2</th>
<th>Turbine 3</th>
<th>Turbine 4</th>
</tr>
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<tbody>
<tr>
<td>Inlet Pressure (MPa)</td>
<td>1.9</td>
<td>0.69</td>
<td>1.88</td>
<td>1.9</td>
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<tr>
<td>Inlet Temperature (K)</td>
<td>45.9</td>
<td>20.6</td>
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<td>80</td>
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<tr>
<td>Outlet Pressure (MPa)</td>
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<td>0.12</td>
<td>0.45</td>
<td>0.53</td>
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<tr>
<td>Outlet Temperature (K)</td>
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<td>12.4</td>
<td>6.4</td>
<td>56.5</td>
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<td>Expected Efficiency</td>
<td>0.76</td>
<td>0.77</td>
<td>0.67</td>
<td>0.74</td>
</tr>
<tr>
<td>Mass Flow Rate (g/s)</td>
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<td>100</td>
<td>110</td>
<td>110</td>
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<tr>
<td>Power (kW)</td>
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<td>4.1</td>
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<td>13.85</td>
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<td>Speed (rpm)</td>
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<td>105000</td>
<td>110500</td>
<td>184000</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>28</td>
<td>40</td>
<td>15</td>
<td>35</td>
</tr>
</tbody>
</table>

There is a vacuum insulated valve box to install the cryogenic valves at the liquid helium temperature level. A 10,000 liter dewar is used for the storage of liquid helium. It can increase the cooling capacity of the plant when the heat load increases, and supply other laboratories with liquid helium.

Control dewar

There are two control dewars, one is at 4.5 K and the other is at 3.5 K. They absorb the heat loads taken out by the SHe from the magnets, act as the phase separator of helium, and return the cold helium gas to the refrigerator.

The TF magnets and PF magnets are cooled by two independent helium loops. The TF coils are hydrodynamically connected in parallel, which requires a total mass flow rate of 260 g/s SHe. Such a large mass flow rate is provided by a supercritical helium circulation system. Two supercritical helium circulators are installed together with the 3.5 K control dewar. One acts as a spare in case the operating pump goes out of service.

The PF magnets are cooled by supercritical helium from the J-T turbine T3. 110 g/s of helium are cooled to 3.8 K in the control dewar before entering the PF coils.

CONCLUSIONS

The design of the 2 kW/4K helium refrigerator for HT-7U superconducting tokamak has been completed. The basic capacity of the refrigerator is 1050 W/3.5 K + 200W/4.5K + 13 g/s LHe + 13 kW/80 K. The construction of the system is now in progress. Screw compressors and the oil removal system have already been installed. The turbines have been fabricated and transferred to CASIPP. The heat exchangers are in fabrication. The coldbox and valve box are under designing. It is expected to complete the refrigerator construction in 2003.

ACKNOWLEDGMENTS

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REFERENCES

[1] Yuanxi Wan, etc. Overview of steady state operation of HT-7 and present status of the HT-7U project, Nuclear Fusion, Vol.40, No.6