Commissioning of the JT-60SA helium refrigerator

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Abstract. The JT-60SA project will use superconducting magnets to confine the plasma and achieve a plasma current with a typical flat top duration of 100 second in purely inductive mode. The helium refrigerator has an equivalent cooling power of 9 kW at 4.5 K providing 3.7 K, 4.5 K, 50 K and 80 K for the diverter cryopump, the superconducting magnets, the HTS current leads, and the thermal shields, respectively. This paper summarizes the JT-60SA helium refrigerator commissioning activities aiming at successful operation of heat load smoothing technology to manage the 12 kW heat pulses by 9 kW cooling power using a 7000 liter liquid helium.

1. Introduction

The JT-60U is being upgraded to a full-superconducting tokamak referred as the JT-60 Super Advanced (JT-60SA) as one of the JA-EU broader approach projects [1]. The JT-60SA project will use superconducting magnets to confine the plasma and achieve a plasma current with a typical flat top duration of 100 second in purely inductive mode. The helium refrigerator provides 4.4 K, 50 K, and 80 K for the superconducting magnets, the HTS current leads, and the thermal shields(TS), respectively. In addition 3.7 K helium is provided for the divertor cryopumps. The refrigerator consists of warm compressors, a refrigeration cold box, an auxiliary cold box and LN2 and GHe storages.

The refrigerator was manufactured and installed in Naka Fusion institute by Air Liquid Advanced Technology, France in September 2015 [2]. The commissioning started in October 2015 and has been finished in October 2016. During the commissioning the followings operations were tested; automatic cool-down and warm-up, automatic purification, the total cooling capacity, stable operation in the...
Short Term Stand-by (STS) and baking (BAK) mode, nominal pulse modes and quench sequence, regeneration sequence of the divertor cryopanels. In addition, automatic transition tests between all defined stationary modes, such as 80 K stand-by mode, STS mode, BAK mode, TF nominal mode, Magnet nominal mode, etc. have been also checked and validated during the commissioning.

2. JT-60SA helium refrigerator

The JT-60SA refrigerator is the world largest class helium refrigerator for a fusion device with an equivalent cooling power of 9 kW at 4.5 K[3,4]. One of the feature of the refrigerator is the capability of the large transient heat pulses by the heat load smoothing technology utilizing a 7000 liter liquid helium damper. The helium bath absorbs the pulse heat by a temporary temperature increase and subsequent vaporization of helium liquid [5]. After the pulse, the refrigerator starts liquefying to recover the liquid level to the original for the next pulse. The JT-60SA refrigerator also has the capability of supplying 50 K for HTS-CL, and the temperature-controllable automatic cool down and warm-up, which is the first challenge by a liquid nitrogen pre-cooled refrigerator.

Figure 1 shows a whole view of the JT-60SA helium refrigerator. The refrigerator will use 1250 m3 gaseous helium stored in 5 helium storage vessels. There is an extra helium gaseous tank dedicated for magnet quench, which is specially designed to avoid local excess cooling of the tank by large amount of cold quench helium gas. In the quench tank, a perforated nozzle is inserted to spray the gas homogeneously. For pre-cooling of the refrigerator in the commissioning, 65000 liter liquid nitrogen tank is used. Because even STS mode consumes over 30000 liter nitrogen a day, which is more than half of the tank capacity, an additional 100000-liter liquid nitrogen tank is planned to install next to the existing 65000 liter tank for more stable and reliable tokamak operation.

![Figure 1](image1.jpg)

**Figure 1.** A whole view of the JT-60SA refrigerator

**Figure 2.** A layout and pictures of the refrigerator and its components. A top figure is a whole layout with close-up of the cold boxes and compressors. Corresponding pictures for components are given below the layout drawing.
Table 1 shows the main cryogenic user the JT-60SA refrigerator provides the cooling powers. The 650 ton superconducting magnet consists of the Toroidal Field Coil(TFC), the Central Solenoid(CS), and the Equilibrium Field Coil(EFC) at 4.5 K is the dominant mass of the cryogenic user. The coil...
mass consists of its Winding Pack(WP) and the structure(STR). The second dominant mass is the thermal shield of 100 ton at 80 K. Table 2 shows requirements of the JT-60SA refrigerator in 3 different operation modes, Plasma Operation State(POS), Short Term Standby(STS), Baking mode (BAK). The POS corresponds to the pulse heat operation, which is most demanding operation. The STS mode is operated during the night every day after daily operation.

**Table 1. Main cryogenic users mass**

| Cryogenic user | TFC (STR/ WP) | CS (STR/ WP) | EFC (STR/ WP) | Total magnet | Cryopump panels/baffles | Thermal shield |
|----------------|---------------|--------------|---------------|--------------|-------------------------|----------------|
| Weight(ton)    | 280/100       | 33/60        | 64/114        | 650          | 1.3                     | 100            |
| Material       | Stainless steel/Cu | Stainless steel/Cu | Stainless steel/Cu | Stainless steel/Cu | Stainless steel        | Stainless steel |

**Table 2.** shows requirements of the JT60-SA refrigerator in 3 different operation modes.

| Cryogenic user          | Temperature           | POS            | STS            | BAK            |
|-------------------------|-----------------------|----------------|----------------|----------------|
| Thermal shields, cryopump baffles | 80 K (140 K for BAK) | 42000 W        | 41300 W        | 135000 W       |
| HTS current leads       | 50 K                  | 25 g/s         | 13 g/s         | 0 g/s          |
| TFC and structure       | 4.4 K (20 K for BAK)  | 1794 W         | 1270 W         | 2260 W         |
| CS and EFC              | 4.4 K (20 K for BAK)  | 1850 W         | 600 W          | 1130 W         |
| Cryopump panel          | 3.7 K                 | 84 W           | Regeneration   | 0 W            |

**Figure 3.** Process diagram of the JT-60SA refrigerator
During the night STS, the cryopump panel planned to be regenerated for 7 hours. Once a month, the plasma vacuum vessel of the JT-60SA plans to be in BAK mode at 200 degree in Celsius for one week. During the BAK, the thermal shield outlet temperature goes up to 140 K.

Figure 3 shows the process diagram of the JT-60SA refrigerator in order to achieve the requirement in table 2. Stored gaseous helium, first, is transferred to the 4 KAESER compressor units to be pressurized up to 1.5 MPa. The pressurized helium is pre-cooled with liquid nitrogen, and expanded by 3 turbines exchanging the heat by the heat exchangers. The helium is supplied to the 4.4 K damper with volume of 7000 liters and 3.7 K damper. The 4.4 K damper pressure and temperature is controlled by the cold compressor located at top left of the damper. This cold compressor also plays very important role for control of the pulse heat operation. The JT-60SA refrigerator has 2 circulators for TFC/Structures and PF coils as shown in Figure 3. In order to obtain 3.7 K, the refrigerator has the VLP(Very Low Pressure) pump at room temperature.

3. Tests in commissioning

In the commissioning of the JT-60SA refrigerator, following modes were tested, automatic cool-down and warm-up with temperature controlling, automatic purification, total 6.6 kW cooling capacity, stable operation in STS and BAK, pulse tests, quench sequence. In this paper, result of cool-down and pulse test are briefly reported. Other tests will be presented elsewhere.

3.1. Cool-down

One of the conditions of the temperature control of cool-down is that during the cool down the temperature of the magnets is maintained 20K - 50K lower than that of the thermal shields down to 80 K, in order to trap all impurities on the colder surfaces and maintain the emissivity of the polished TS surface. The second condition is that the temperature difference between inlet and outlet temperature (of TS and Coil) is always smaller than 40 K to avoid excess thermal stresses. In cool-down, heats were applied to the coil and the TS to simulate the Tokamak to some extent. Results of cool down test is shown in Figure 4. In the cool-down, the coils are firstly cooled followed by the thermal shields active cooling as is designed. It is found the temperature of the coil is always 20 K below the temperature of the thermal shields. It is also found that the temperature difference between outlet and inlet temperature of the thermal shields are always below 40 K. It was concluded that cool down test was successfully performed by defined temperature control.

![Figure 4. Temperature evolutions of the TS and coil in cool down](image)

3.2. Pulse test

JT-60SA shall be capable of investigating several design scenarios. There are mainly 2 kinds of repetition time; 1800 second for 60 second pulse and 3000 second for 100 second pulse. Figure 5
shows schematic of the pulse heat control. In this paper, the result of 60 second pulse is briefly presented. In the pulse tests, a decayed heat profile after travelling all the way in the transfer line is calculated to input to 2 loops for TF and PF in the ACB as shown in top in Figure 5.

The pulse heat load for each loop consists of the conductor AC loss, conductor joint heat, nuclear heating, the structure eddy current in addition to the steady heat load such as the conduction and the radiation heat loss [6]. When the pulse arrives the damper of the refrigerator, the pulse heat will increase the damper temperature and the damper pressure increases accordingly. Subsequently, the cold compressor slows down its speed to keep the energy in the damper. This is mainly to keep the pressure in the low pressure line as stable operation of the compressors as possible. The increased damper temperature expands the liquid by thermal expansion by several percent. After passing the pulse, the cold compressor start speed up its speed again to go back to the initial conditions. In the right bottom of figure 5, it is found the damper pressure and the temperature with liquid level successfully recovered its initial position after the pulse as is required in the criteria.

![Figure 5. Schematic of pulse heat control(left), input heat pulses(right top), and test results(right bottom)](image)

In the commissioning, auto purification test, 6.5 kW capacity test, quench tests, and cryopump regeneration test are also performed to confirm the required specification of the JT-60SA helium refrigerator.

4. Utility consumption

For the commissioning, 13500 Nm$^3$ (2.4 tons) gaseous helium was first supplied to the refrigerator. Total consumption of the liquid nitrogen and electrical power during the commissioning reaches 1300 m$^3$ and 6700 MWh, respectively. The flow rate of the cooling water is 200 m$^3$/h and 12 m$^3$/h for the cycle compressors and turbines(pumps, circulators), respectively. Current helium inventory is 9500 Nm$^3$ (1.7 tons), which is 70% of initial inventory.

Table 3 shows resulted consumption of electrical power and liquid nitrogen in different mode of the refrigerator. It is found these result are in good agreement with the design values. In the cool-down of the commissioning, the refrigerator consumes rather small amount of nitrogen because no heat
loads from coils and thermal shields are simulated by heaters. This should go up to around 1200 liter/hour with Tokamak, which is the same as the STS. In the STS and the BAK in table 3, the estimated heater powers were applied to the coils and the thermal shields to see the stability of the refrigerator. In the BAK test, 10 trucks(capacity of 8000 liters) continuously deliver the LN2 in a day.

Table 3. Utility consumption in each mode

| Utility  | unit | Cool-down | STS  | BAK  | POS  | Warm-up |
|----------|------|-----------|------|------|------|---------|
| LN2      | liter/hour | 400      | 1200 | 3400 | 1400 | 400     |
| Electricity | MW | 1.6       | 2.1  | 2.0  | 2.6  | 1.9     |

5. Conclusions
All the tests planned in the commissioning of the JT-60SA helium refrigerator was successfully finished as follows:

- Automatic cool down was performed under the temperature conditions of the coil and the thermal shields.
- Pulse heat was repeatedly applied at 4.4 K loops. It was confirmed increased temperature, liquid level, vapor pressure in the damper were recovered to the initial level within 30 minutes.
- Other tests such as the 6.5 kW cooling capacity test, STS/BAK tests with stability criteria for 36 hours, quench sequence test, were all performed successfully.

It can be concluded that heat smooth technology was successfully demonstrated to manage the 12 kW heat pulse with only 9 kW cooling power using 7000-liter liquid helium damper.

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