Integration and Commissioning of a Full Localization 250 W @ 4.5 K Helium Refrigerator at TIPC

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Abstract: A full Localization 250W@4.5K helium cryogenic refrigerator, composed of a helium screw compressor and its oil-removal subsystem, six plate-fin cryogenic heat exchangers, two high speed turbine expanders, eight pneumatic valves and a vessel with heat load, was developed at TIPC. The high and low pressure can be maintained stable by adjusting the PI parameters of pneumatic valves. Commissioning full localization 250W@4.5K refrigerator system is discussed. 300–4.5K cool-down processes of cryogenic heat exchangers are present. The optimized cooling capacity of this refrigerator system is up to 317W at liquid helium temperature.

1. Introduction

Particle physics research, cooling of cavities or superconducting magnets require large cryogenic refrigeration units to cool down. The LHC proton beams accelerator at CERN requires superconducting magnets, which are cooled down at 1.9 K and maintained superconducting over a 27 km ring by large scale helium cryogenic plants [1-2]. Larger cryogenic systems with high demands in terms of development effort, performance and operational availability is ongoing. Conceptual design of the cryogenic system for the high-luminosity upgrade of the LHC has been proposed [3]. The ITER cryogenic system includes three identical liquid helium (LHe) plants with a total average cooling capacity equivalent to 75 kW at 4.5 K [4]. In China, the domestic requirements of research application are becoming urgent in recently years. Hundreds of watts refrigeration capacity at liquid helium temperature at TIPC/CAS has been developed to satisfy these demands [5]. In this paper, a full Localization 250 W@4.5 K helium refrigerator was successfully developed and discussed in details.

2. Integration of 250W@4.5K large scale helium cryogenic refrigerators

The process flow diagram of full localization 250W@ 4.5K helium cryogenic refrigerator is shown in Figure 1. The system consists of a helium screw compressor (C), six heat exchangers (HX1-6), two turbine expanders (E1 and E2), eight pneumatic valves (V1-V4, V7-V10), switch valves (V5-V6), a J-T valve (V9) and a vessel with a heat load (HL). High-purity helium from the buffer tank is sucked into the compressor and compressed to high pressure. Then it goes through the three-stage oil removal subsystem to filter the oil into ppb level. When the purity of helium in the compressor subsystem
reaches requirements, V5 and V6 are opened and the cool-down process of the cold box starts. In cold box, it is pre-cooled by liquid nitrogen and passes through HX1 and HX2. After that, it would be taken as two parts. The first part is expanded by turbines E1 & E2 and goes back to the low pressure sides. The speed of E1 & E2 is controlled by adjusting the opening of V7. The second part goes through HX3-HX6 and V9 into the vessel with HL, which can evaluate the cooling capacity of the cryogenic system. Finally, the second part combines with the first part at HX5 and returns to the compressor C.

![Image 1](https://example.com/image1.jpg)

**Figure 1.** Process flow diagram of the 250W@ 4.5K helium cryogenic refrigerator

![Image 2](https://example.com/image2.jpg)

**Figure 2.** 3-D configuration of 250W@ 4.5K helium cryogenic refrigerator

Based on process flow diagram in figure 1, 250W@ 4.5K helium cryogenic refrigerator was designed and developed, a 3-D configuration of which is shown in figure 2. A helium screw compressor with 150 kW rated power and variable frequency driver 20~50 Hz is used to supply 0~57 g/s mass flow rate and 1~14 bara pressure range. An oil removal subsystem can effectively remove the oil up to the level of 10 ppb at the output. A cold box with a diameter of 1.8 meter and a height of 3 meter is constructed, into which is inserted HX1-HX6, E1-E2 and cryogenic tubes. Cernox® thin film resistance cryogenic temperature sensors CX-1050 are applied at the input and output of HX1-HX6 and E1 and E2 to measure the local temperature. Typical accuracy of Cernox® temperature sensors is lower than ±10mK and long-term stability is ±25mK. The isentropic efficiency can be acquired by
the input and output of local temperature and pressure of turbine expanders E1 and E2. The picture of integrated 250W@4.5K helium cryogenic refrigerator is presented in figure 3.

Figure 3. picture of the 250W@4.5K helium cryogenic refrigerator, (a) a helium screw compressor and an oil removal subsystem, and (b) a 4K cold box and a vessel with a heat load

3. Commissioning of 250W@4.5K large scale helium cryogenic refrigerator

3.1 Commissioning the stability of high and low pressure

In the helium cryogenic refrigerator, the helium screw compressor runs to 20 Hz in 2-3 minutes, when it receives the start-up signal. The high pressure is controlled by the discharge valve V1 and the charge valve V2, while the low pressure is controlled by the pneumatic valves V3 and V4. By adjusting the PI parameters of pneumatic valves V1~V4, the high and low pressure of the system can be maintained stable. The relationship of mass flow and the compressor speed is: 7 g/s @ 20 Hz, 57 g/s @ 50 Hz
rated condition. Dynamic process of high and low pressures of helium screw compressor is shown in figure 4.

3.2 Cool-down to 4.5K
The temperature profile of 300–4.5K cool-down processes at TI2122, TI2131, TI2141, TI2151a and TI2161 at high pressure side at the output of cryogenic heat exchanger HX1, HX3–HX6 are given in figure 5. The cold box is precooled, and HX1 is the first to reach the predetermined temperature 78 K at TI2122. After 10 hours, HX3–HX6 in the cold box is cooled down and the system achieves quasi-steady state. The temperature at TI2160 is up to 4.5K. The isentropic efficiency can be acquired by the input and output of local temperature and pressure of turbine expanders E1 and E2. The highest speed and isentropic efficiency of E1 and E2 is up to 220000 rpm and 65%, respectively.

![Figure 5](image)

Figure 5. the temperature profile of 300–4.5K cool-down processes at TI2122, TI2131, TI2141, TI2151a and TI2161 at high pressure side at the output of cryogenic heat exchanger HX1, HX3–HX6

![Figure 6](image)

Figure 6. (a) the stretch of the vessel with heat load, (b) the cooling capacity including cooling temperature and cooling power of helium cryogenic refrigerator.
3.3 Cooling capacity evaluation

The vessel with a heat load EH4100 and a cryogenic temperature sensor TI4100 is described in figure 6 (a) in detail. By maintaining the high pressure of system and the liquid helium level LI4100 of the vessel stable, the cooling temperature and the cooling power are measured by TI4100 and EI4100, respectively, which is shown in figure 6(b). The value $W_c$ of EI4100 equals to the electricity power $W_e$ minus the dissipation of heating power $W_d$ caused by external copper wire, which is given by

$$W_c = W_e - W_d = \frac{U_e^2}{R_e} - I_d^2 R_d$$

(1)

where $U_e$ and $R_e$ are the voltage and resistance of the heat load, $I_d$ and $R_d$ are the current and resistance of the external copper wire, respectively.

The maximal cooling capacity of this helium cryogenic refrigerator is up to 317 W at liquid helium temperature. After two hours, by changing the electricity power of the heat load, the cooling capacity of 250 W @ 4.5 K is also tested to evaluate the performance of this helium cryogenic refrigerator.

4. Conclusion

A full Localization 250W@4.5K helium cryogenic refrigerator, composed of a helium screw compressor and its oil removal subsystem, six plate-fin cryogenic heat exchangers, two high speed turbine expanders, four pneumatic valves and a liquid helium Dewar with heat load, has been successfully developed for the refrigeration mode. The commissioning of the refrigerator system has been well done by proper PI control strategy. The maximal cooling capacity is up to 317W at liquid helium temperature, which will be used in the research application field.

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References

[1] Lebrun Ph 2006 Proceedings of the 21th International Cryogenic Engineering Conference, Praha, Czech Republic.
[2] Tavian L 2007 IEEE/CSC & ESAS European Superconductivity News Forum
[3] Brodzinski K, Claudet S, Ferlin G, Tavian L, Wagner U, Van Weelderen R 2015 Physics Procedia 67: 60 – 65
[4] Fauvea E, Bonnetona M, Chalifoura M, Changa H S, Chodimellaa C, Monnereta E, Vincenta G, Flavienb G, Fabreb Y, Grillotb D 2015 Physics Procedia 67: 42 – 47
[5] Xie X, Wu D, Yang S, Deng B, Pan W, Li Q, Gong L 2018 Energy Procedia