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Cool Down Results from a Fully Localized 250W @ 4.5 K Helium Refrigerator at TIPC

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Abstract. The 250W@4.5K refrigerator, which is localized at Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, is composed of the compressor, turbo-expanders, cryogenic heat exchangers, JT valve and electric heater. This refrigerator operates stably and meets the design target after the test and commission. This paper describes the investigation on the optimization of the cool down scheme and the performance analysis of the refrigerator.

1. Introduction

Large scale cryogenic helium refrigerators are widely used in the large scientific facilities, such as the international thermonuclear experimental reactor[1] (ITER), the electron-positron collider[2] (KEKB) in Japan KEK laboratory, the Tera eV Energy Superconducting Linear Accelerator[3] (TESLA) in Germany DESY national laboratory, the Peking University Superconducting Accelerator Facility[4] (PKU-SCAF). These refrigerators provide liquid helium @4.5 K or superfluid helium @1.6K -2.17K to cool down these scientific instruments and keep their key parts in the superconducting condition to make sure them to work steady.

A 250W@4.5K refrigerator is developed by Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences. In this paper, the cool down schemes of the refrigerator are compared and optimized. Then the performance analysis is conducted.

2. Experimental setup of the 250W@4.5K refrigerator

The 250W@4.5K refrigerator, localized at Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, is composed of a compressor, two turbo-expanders, six cryogenic heat exchangers, a JT valve, a heater, and some control valves. The process flow diagram is shown in Figure 1. The turbines which work at 225,000 rpm are equipped static gas bearings. The refrigerator operates at 10bara of the high pressure and 1.05bara of the lower pressure with a liquid nitrogen pre-cooling system. This refrigerator was designed and manufactured in TIPC.

Nomenclature			
e	Specific exergy	subscripts	
E	Exergy	0	Reference status
h	Specific enthalpy	x	Calculated status
m	Rate of mass flow	t	Flow through the turbines
Q	Heat flux	J	Flow through the JT valve
s	Specific entropy	leak	Heat leakage
T	Temperature	cp	Cooling power
η	efficiency	cb	Cold box

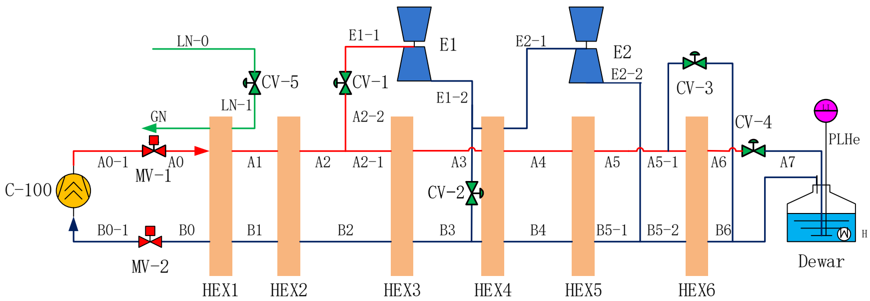

Figure 1. The basic process flow diagram of the 250W@4.5K refrigerator

3. Optimization of cooldown process

The cooling power at 4.5K of this refrigerator is 280W in the experiment, which has reached the design value. The efficiencies of the turbines are over 65%. However, the time of the cooldown process is about 23 hours, which is too long for operators. The trends of the measured temperatures are shown in Figure 2.

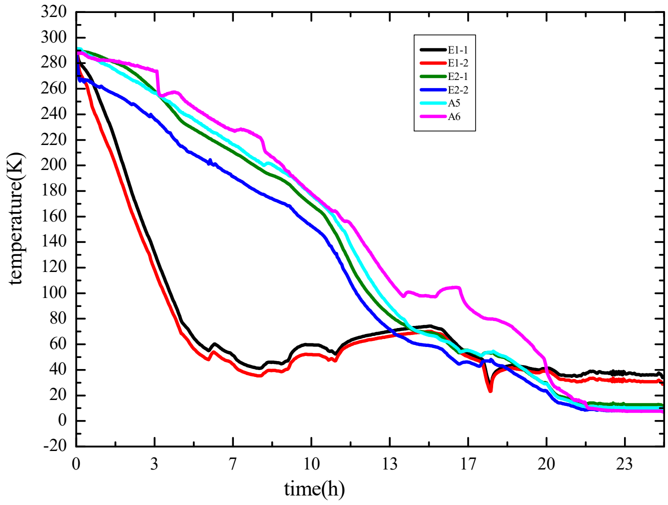

Figure 2. Variation of measured temperatures versus time

In the cooldown process, the nitrogen and turbines provide the cooling power to cool down the cold box and the dewar. The dewar is cooled down with the cold box simultaneously. It costs too much time because the heat capacity is large.

A method with a by-pass from the output of the dewar to the output of the first stage heat exchanger in the lower pressure side is taken, which can avoid the thermal shock when the cold box and dewar are cooled down in series. An optimized flow scheme with the by-pass is shown in Figure 3. The cool down process was tested. The trends of the temperatures are shown in Figure 4.

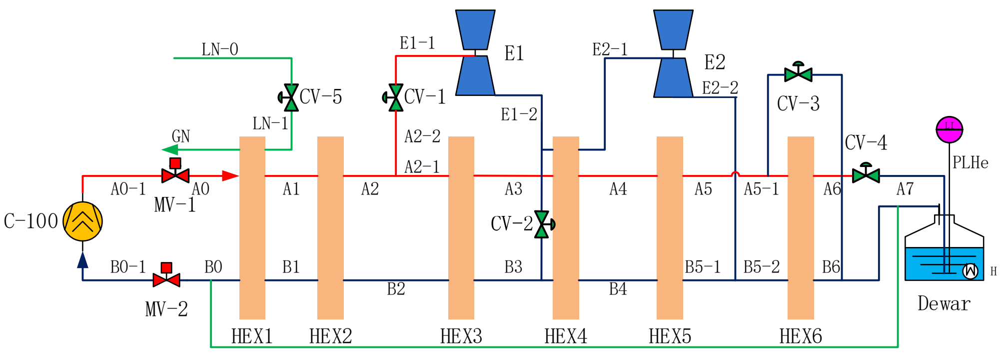

Figure 3. The optimized process flow diagram with the by-pass

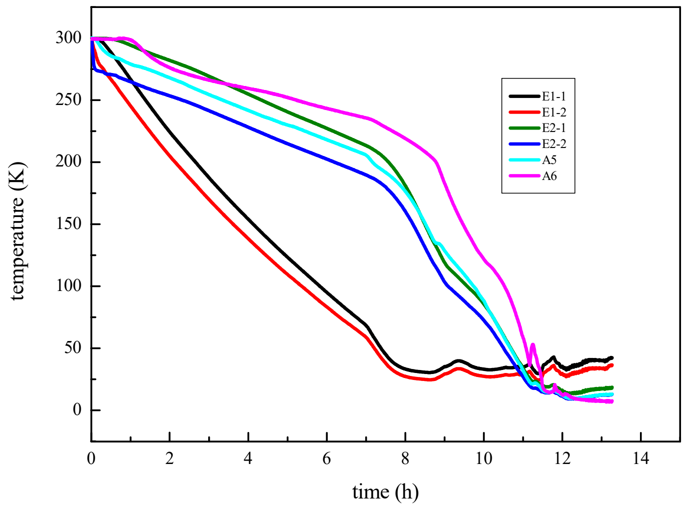

Figure 4. Variation of measured temperatures versus time in the optimized scheme

Compared with the measurement without the by-pass, the time decreases by about 10 hours, which means that the method with the by-pass improves the performance of the refrigerator.

4. Performance analysis

The reference state for the exergy analysis is at $T_0 = 300K$ and $p_0 = 1bara$. Exergy of helium at other state is obtained from the date base of NIST. Exergy is calculated through the following equation,

$$e_x = h_x - h_0 - T_0(s_x - s_0)$$

So the exergy of each point is shown in the Table 1.

Table 1 Entropy, enthalpy and exergy in selected points

Point	A1	B1	E1-1	E1-2	A3	B3	E2-1	A4
s(kJ kg^{-1} K^{-1})	19.76	24.23	15.03	15.50	14.09	18.56	11.86	10.43
h(kJ kg^{-1})	419.46	408.60	174.16	149.75	149.20	149.55	80.05	77.96
e(kJ kg^{-1})	2401.22	1049.23	3575.99	3408.40	3831.87	2491.82	4431.33	4858.6
Point	B4	E2-2	A5	B5-1	B5-2	A6	B6	
s(kJ kg^{-1} K^{-1})	14.69	13.31	8.24	13.36	13.41	3.32	7.67	
h(kJ kg^{-1})	79.00	64.01	51.74	64.56	65.01	3.32	28.26	
e(kJ kg^{-1})	3581.65	3981.63	5488.51	3965.45	3952.48	6916.14	5638.73	

The helium flow rates though turbines and JT valve are calculated by the energy balance. When the refrigerator works at a stable state, the temperatures and pressures are measured. The flow into the cold box is 45.08g/s.

The exergy losses in the main parts of the refrigerator are calculated from the following equations.

1) Exergy loss caused by hydrostatic gas bearings:

$$\Delta E_B = \dot{m}_B(e_{A0} - e_{B0}),$$

2) Exergy loss in the first stage exchanger:

$$\Delta E_I = \dot{m}_{\mathrm{LN}}(e_{LN-0} - e_{GN}) + \dot{m}_{all}(e_{A0} - e_{A1} + e_{B1} - e_{B0}),$$

3) Exergy loss in the second and third stage exchangers:

$$\Delta E_{II-III} = \dot{m}_{all}e_{A1} - \dot{m}_t e_{E1-1} - \dot{m}_J e_{A3} + \dot{m}_{all}(e_{B3} - e_{B1}),$$

4) Exergy loss in the fourth stage exchanger:

$$\Delta E_{IV} = \dot{m}_t(e_{E1-2} - e_{E2-1}) + \dot{m}_J(e_{A3} - e_{A4}) + \dot{m}_{all}(e_{B4} - e_{B3}),$$

5) Exergy loss in the fifth stage exchanger:

$$\Delta E_V = \dot{m}_J(e_{A4} - e_{A5}) + \dot{m}_{all}(e_{B5-1} - e_{B4}),$$

6) Exergy loss in the sixth stage exchanger:

$$\Delta E_{VI} = \dot{m}_J(e_{A5} - e_{A6} + e_{B6} - e_{B5-2}),$$

7) Exergy loss in the first stage turbine:

$$\Delta E_{E1} = \dot{m}_t(e_{E1-1} - e_{E1-2}),$$

8) Exergy loss in the second stage turbine:

$$\Delta E_{E2} = \dot{m}_t(e_{E2-1} - e_{E2-2}),$$

9) Exergy loss in the JT valve:

$$\Delta E_{CV-4} = \dot{m}_J(e_{A6} - e_{A7}),$$

10) Exergy loss caused by the heat leakage in the dewar:

$$\Delta E_{leak} = \left(\frac{\mathrm{T}_0}{T_{A7}} - 1\right) Q_{leak}$$

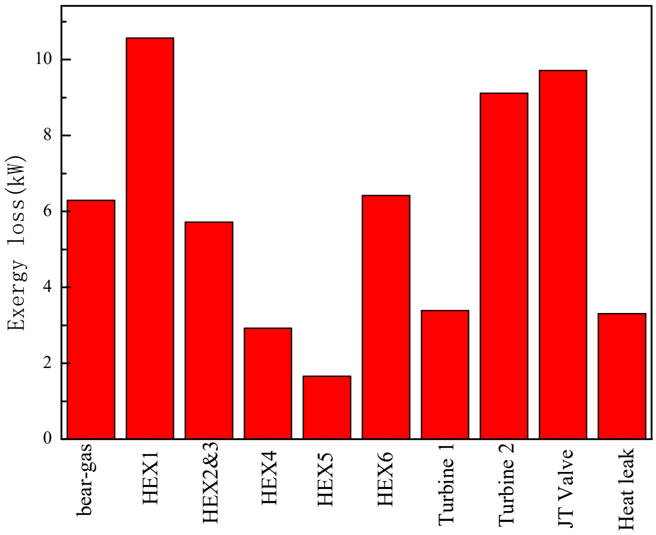

Figure 5. Exergy loss in different parts of the cold box

Figure 5 shows the calculated results of the exergy losses in the main parts. Except the JT valve, the optimization in the type of the gas-bearing system, the first stage exchanger, the 2nd and 3rd stage exchanger, the 6th stage exchanger, and the 2nd turbine are the next work to do to improve the performance of the refrigerator.

For cold box, the exergy efficiency is calculated as follows,

$$\eta_{cb} = \frac{\left(\frac{\mathrm{T}_0}{T_{A7}} - 1\right) Q_{cp}}{\dot{m}_{\mathrm{LN}}(e_{LN-0} - e_{GN}) + \dot{m}_{all}(e_{A0} - e_{B0})} = 26.4\%$$

The compressor (LGD220) used in this refrigerator is supplied by the Wuxi Compressor Co., LTD. In the experiment, the electric power consumed by the compressor is 150kW. The coefficient of performance of the refrigerator is calculated as follows,

$$COP = \frac{280W}{150kW} = \frac{1}{535.7} \quad W/W$$

This performance is lower than that of the similar plant from other company, such as the LR70 refrigerator and LR280 refrigerator of Linde Kryotechnik AG[5]. The COP of LR70 is 1/395, and the COP of LR280 is 1/286. Compared with similar plant from Linde, there are some shortcomings of the refrigerator in TIPC. The deeply analysis and improvement in the refrigerator is conducting.

5. Conclusion

In this paper, the fully localized 250W@4.5K helium cryogenic refrigerator is introduced. The optimization of cooldown process is conducted and the exergy analysis is performed. The results show the optimized scheme with the by-pass efficiently decreases the cooldown time. The exergy efficiency of the cold box is 26.4%, and the COP of the whole refrigerator is 1/535.7 W/W. Compared with the similar plant from other company, the performance of this refrigerator need to improve. Higher efficient refrigerator is our next goal, and the related work is conducting.

Acknowledgement

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