Balanced design and commissioning of a 500W/4.5K helium refrigerator and its liquefier

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Abstract. A 500W/4.5K helium refrigerator for ADS (Accelerator Driven Subcritical) project of CAS (Chinese Academy of Sciences) has been designed. The functional requirements and process analysis of this helium refrigerator are described. Based on the regulation of the high pressure, a balanced design between refrigeration capacity and liquefaction capacity for equal Carnot work with the same high efficiencies is presented. The constraints of components and operation strategies in refrigeration mode and liquefaction mode are discussed. Commissioning results indicated that this 500W/4.5K helium refrigerator can provide 5.74g/s (or 165L/h) liquid helium in liquefaction mode or 550W at 4.5K in refrigeration mode with the respective FOM (Figure of Merit) of 14% or 13.2%. Existing problems were analyzed and discussed through comparing the theoretical calculation and experimental data, and some suggestions are given at the end of this paper.

1. Introduction

In general, the helium cryogenic system can be worked as a refrigerator or a liquefier. As a helium liquefier, output liquid exits the system along with the latent and sensible heat. However, a helium refrigerator is a closed system where the latent heat is absorbed only. The boil-off gas returns to the compressor through the counter-flow heat exchangers to retrieve the sensible heat. At atmospheric pressure, latent heat per kg of liquid helium is about 20 kJ, while the sensible heat is about 1540 kJ per kg [1]. Therefore, there are differences in configuration as well as design and operating parameters between liquefiers and refrigerators.

For an equal Carnot work, an ideal helium cryogenic system can support 100W of 4.5K refrigeration or 1 g/s of 4.5K liquefaction. In fact, a system designed as a refrigerator but used as a liquefier will not be able to provide the Carnot equivalent liquefaction capacity provided in refrigeration mode due to the expansion limited. A system designed as a liquefier but used as a refrigerator will not be able to provide the Carnot equivalent refrigeration capacity provided in liquefaction mode due to the HXs limited [2].

The balanced design of a 500W/4.5K helium refrigerator and its liquefier is presented through the regulation of high pressure. It can provide 500W at 4.5K refrigeration capacity or 5.17g/s liquefaction rate in design mode for equal Carnot work. The comparisons of turbines and heat exchangers in different modes are shown. The operation strategies and commissioning results in refrigeration and liquefaction mode are analyzed. Some existing problems and discussions complete the paper.

2. Description of a 500W@4.5K helium refrigerator

The Institute of Plasma Physics of CAS undertook a sub-project of ADS system, supported by the Special Fund for strategic pilot technology of CAS. The task was research and development of a
500W/4.5K helium refrigerator, which can provide the necessary cryogenic environment for the test of superconducting magnets or as a helium liquefier.

2.1. Functional requirements of the 500W@4.5K helium refrigerator
According to heat load, the desired helium refrigerator can provide refrigeration capacity of 500W at 4.5K in refrigeration mode, or liquefaction rate of 150 L/h in liquefaction mode. The detailed requirements are listed as below:

(1) Operate in pure refrigeration mode, pure liquefaction mode or the refrigeration/liquefaction mix mode.

(2) Provide the supercritical helium gas interface at 5bar for the forced-flow cooling.

(3) Provide the 80K helium gas interface to control the 300K-80K pre-cooling of superconducting magnets independently using Liquid Nitrogen (LN2).

(4) Provide the 80K, 20K and 4.5K bypass streams respectively to utilize the returned cold gas from superconducting magnets during the cool-down process.

(5) Operate automatically in different phases, such as cool-down process, steady-state operation and warm-up process, including interlocks.

2.2. Process analysis of the 500W@4.5K helium refrigerator
500W/4.5K helium refrigerator is classified as a mid-size helium refrigeration plant. The Claude refrigeration cycle of two turbines in series with LN2 pre-cooling is chosen in general. The simplified process flow diagram for 500W@4.5K helium refrigerator is presented in figure 1 [3].

![Figure 1. Simplified process flow diagram of the 500W@4.5K refrigerator.](image)

Low Pressure (LP) helium gas is compressed to High Pressure (HP) helium gas by screw compressor. Then HP helium gas enters the cold box, pre-cooled to 80K in HX1A and HX1B by LN2 and low pressure (LP) helium gas in counter flow. Impurities like nitrogen and oxygen in HP helium gas is absorbed by 80K absorber. With the LN2 pre-cooling unit, superconducting magnet can be realized the 300K-80K cool-down process respectively through mixed gas between 300K and 80K helium gas.

In HX2, HP helium gas is split into two parts: turbine stream and Joule-Thomson (JT) stream. The turbine stream gets expanded in turbine T2230. After a further cool down in HX3, it enters turbine T2250 which is expanded to low pressure and finally joins into the returned JT stream. The JT stream is cooled down by HX2, HX3 and HX4. Impurities like neon and hydrogen is removed by 20K absorber. JT stream is cooled down in HX5A and throttled to 5bar, then enters the final heat exchanger.

In liquefaction mode, the JT stream is throttled further to LP in CV2272 before the two-phase helium stream leaves the cold box into Dewar. Vapour gas from the Dewar, re-enters to cold box through CV2190. The return gas is warmed up in HX5 before it joins the turbine cycle gas.
LP stream is warmed in counter flow by the HP stream in heat exchangers and enters the suction line of the compressor.

In refrigeration mode, JT stream provides the supercritical helium gas for superconducting magnets through CV2275. The gas returned from superconducting magnets re-enters to cold box through CV2120, CV2150 or CV2180 according to the temperature TI2185 in order to utilize the cooling power and shorten the cool-down time.

3. Balanced design of thermodynamic cycle for the 500W@4.5K helium refrigerator

In general, the thermodynamic calculation of refrigerator/liquefier is optimized through the static simulation based on the different objective function with independent variables [4]. The design of thermodynamic cycle consists of the pressure cycle, temperature cycle and mass-flow cycle considering the efficiency and the effectiveness of real components, such as compressor, turbine expander and heat exchanger.

3.1. Thermodynamic Calculation in Liquefaction Mode

In order to construct the helium refrigerator or liquefier, certain constraint conditions in thermodynamic calculation have been made: (1) Maximum pressure is 15bar according to the one-stage screw compressor, and the isothermal efficiency is 50% and the maximum electric power is 250kW. (2) Turbines of ATEKO company are chosen, and the isentropic efficiencies are 72% in design mode and not less than 70% in off-design mode. (3) The minimum temperature difference of heat exchanger is not less than 0.2K to reduce the size of the heat exchanger. The heat leak of each heat exchanger is 0.1%~0.7% of total exchanger capacity and the percentage factor increases with decreasing temperature.

(1) Pressure cycle

For medium-sized helium refrigerator or liquefier, one-stage compressor is chosen and the high pressure is from 10~15 bar in general. The discharge pressure is chosen at 13.6 bar and the pressure inlet to the coldbox is 13 bar after the water cooling and oil removal system.

HP is dropped to 12.85 bar after 80K pre-cooling heat exchangers, and then divided into turbine stream and JT steam. For the turbine stream, the inlet pressure to T1 is 12.45 bar after the filter and the outlet pressure of T2 is 1.2 bar. The optimum intermediate pressure is approximately the geometric mean of the highest and lowest pressure. On the other hand, the whole power should be divided to two turbines equally. Therefore combining the pressure ratio and power difference of two turbines, the intermediate pressure is chosen at 6 bar. For the JT stream, HP is dropped to 12.6 bar and throttled to 5bar, then throttled further to 1.2 bar and inlet to helium storage.

For the returned LP stream, the whole pressure drop is chosen at 0.16 bar, and the outlet pressure from the coldbox is 1.09 bar. With the pipes’ pressure drop, the suction pressure of the compressor is controlled at 1.05 bar.

(2) Temperature cycle

The temperature degree is divided into three zones, 300K~80K, 80K~10K and the 10K~4.5K approximately.

For the 300K~80K of LN2 refrigeration stage, the temperature of HP helium gas from the compressor is 310K after water cooling and pre-cooled to 80K by LN2 and the returned cold helium gas in HX1A and HX1B.

For the 80K~10K of turbine refrigeration stage, HP helium gas is cooled down to 41.7 K in HX2A and cooled down to 34 K in T1 expander. Then HP helium gas is cooled down to 15.9 K in HX3 and cooled down to 10.3 K in T2 expander returning to LP stream.

For the 10K~4.4K of JT refrigeration stage, HP helium gas is cooled down to 8.95 K and cooled down to 7.53 K in first stage throttle. Then HP helium gas is cooled down to 6.32 K and throttled further to helium storage.

(3) Mass flow cycle
The mass flow cycle includes the mass flow of JT stream and turbine stream. The mass flow of JT stream is calculated by the liquefaction rate. And the mass flow of turbine stream is optimized by the total UA values of heat exchangers and the FOM.

In liquefaction mode, the suction pressure of compressor is 1.05 bar and the output pressure of compressor is 13.6 bar, the mass-flow of compressor is 71.15 g/s. The electric power is 250 kW and the consumption of LN2 is about 22.3 g/s. The total UA values of heat exchangers are $1.79 \times 10^4$ W/C. The FOM of 500W/4.5K refrigerator in liquefaction mode is 13.7%.

3.2. Thermodynamic Calculation in Refrigeration Mode

For a highly efficient refrigerator and liquefier, main differences are the influences of cryogenic components, especially the turbine expanders and heat exchangers. For turbine expanders, the output power for expanders in a liquefier is higher than that in a refrigerator for the same amount of Carnot work. For heat exchangers, the UA values or NTUs of heat exchangers in a liquefier are smaller than that in a refrigerator due to the unbalanced flow in liquefier and the balance flow in refrigerator [2].

For the thermodynamic calculation, certain constraint conditions in refrigeration mode have been made according the devices’ parameters, especially the turbines and heat exchangers.

3.2.1. Turbines

For an equal capacity refrigerator or liquefier, the refrigeration power of turbines in refrigeration mode is smaller than that in liquefaction mode. Generally speaking, the input pressure and the mass flow of turbines are lower.

The mass-flow coefficient of turbine is a constant in different modes [5], shown in equation (1).

$$K_1 = \frac{m \sqrt{Z_{m} T_{m}}}{P_{m}}$$

Where $K_1$ is a coefficient, $m$, $P_m$, $T_m$ and $Z_m$ are respectively the mass flow, inlet pressure, temperature, and compressibility factor. In addition, the efficiency of turbine is decided by input parameters of turbine, described in equation (2). Therefore, the efficiency of turbine can keep constant almost through regulating rotational speed in certain range [5].

$$\text{Efficiency} = K_2 + K_3 \left( \frac{U}{C_s} \right) + K_4 \left( \frac{U}{C_s} \right)^2$$

where $U = \pi \cdot D \cdot N$, with $D$: Turbine expander wheel diameter and $N$: rotational speed; $C_s = \sqrt{2 \Delta H_s}$, $\Delta H_s$: the enthalpy difference at constant entropy; $K_2$, $K_3$ and $K_4$ are constant coefficients determined by turbine.

3.2.2. Heat exchanger

The requirements of heat exchanger in refrigeration mode are larger than that in liquefaction mode. In this calculation of thermodynamic cycle, the optimization of UA value is independent under different modes. However, the design of every heat exchanger is depended on the parameters of refrigeration and liquefaction mode to meet with the maximum requirements.

3.2.3. Compressor

The compressor is an exceptionally efficient variable speed rotary screw compressor with frequency control which can adjust discharge pressure and mass-flow without dropping the efficiency. However, the maximum electric power is constant. In addition, the minimum discharge pressure is limited by the minimum operation pressure of oil removal system.

In refrigeration mode, the suction pressure of compressor is 1.05 bar and the the output pressure of compressor is 10.6 bar, the mass-flow of compressor is 78.84 g/s. The electric power is 250 kW and
the consumption of LN2 is about 11.4 g/s. The total UA values of heat exchangers are $2.9 \times 10^4$ W/C. The FOM of 500W/4.5K refrigerator in liquefaction mode is 13.9%.

3.3. Comparison of thermodynamic calculation in liquefaction mode and refrigeration mode

The comparison of T-S diagram is shown in figure 2. The high pressure is reduced from 13.6 bar in liquefaction mode to 10.6 bar in refrigeration mode with the input pressure of turbine from 12.45 bar to 8.7 bar. The total mass flow of compressor is increased from 71.15 g/s in liquefaction mode to 78.84 g/s in refrigeration mode with the JT stream from 22.35 g/s to 38.46 g/s.

![Figure 2. Comparison of T-S diagram between refrigeration mode and liquefaction mode.](image)

The total UA values of heat exchangers are increased from $1.79 \times 10^4$ W/C in liquefaction mode to $2.9 \times 10^4$ W/C in refrigeration mode. The comparison of UA value for every heat exchanger is shown in figure 3. The UA value for every heat exchanger in refrigeration mode is much greater than that in liquefaction mode especially the HX1B.

![Figure 3. Comparison of UA values between the refrigeration mode and liquefaction mode.](image)
The design parameters of turbines are dependent on the liquefaction mode. With the dropping of input pressure in refrigeration mode, the mass flow of the turbines is reduced from 48.8 g/s in liquefaction mode to 40.4 g/s in refrigeration mode. The refrigeration capacity of T1 is reduced from 1.97 kW to 0.97 kW with a decrease of about 50.7%. The refrigeration capacity of T2 is reduced from 1.27 kW to 0.71 kW with a decrease of about 44.1%. In order to keep the efficiency of the turbines, the rotational speeds of the turbines must be adjusted to match the optimal characteristic ratio.

Due to the compressor with frequency control, turbines with variable speed and heat exchangers considering different modes, the 500W/4.5K helium refrigerator can provide 5.17 g/s in liquefaction mode or 550W/4.5K in refrigeration mode with almost equal FOM of 13.7% or 13.9% respectively.

4. Commissioning of a 500W@4.5K helium refrigerator

4.1. Commissioning of 500W/4.5K refrigerator in Liquefaction mode

The weight curve of vessel for 500W/4.5K refrigerator in liquefaction mode is shown in figure 4. The figure indicates that this refrigerator can produce liquid helium steadily. During commissioning, the weight of vessel increased from 435.9 kg to 497.9 kg by 62 kg within 3 hours. The testing liquefaction rate was 5.74 g/s or 165 L/h.

![Weight curve of vessel in liquefaction mode](image)

**Figure 4. Weight curve of the vessel in liquefaction mode.**

During the steady phase in liquefaction mode, the output pressure of compressor was 13.1 bar, the mass-flow of compressor was 67.5 g/s. Electric power was 253.6 kW and consumption of LN2 was about 22.27 g/s (or equal power was about 15.64 kW). Therefore, FOM of this 500W/4.5K refrigerator in liquefaction mode is 14%.

Compared with design parameters, the mass flow of compressor is less than the design value (71.2 g/s) by 3.7 g/s. The mass flow of turbine is 45.2 g/s, less than the design value (48.8 g/s) by 3.6 g/s. Because the input pressure of turbine is operated at 12.2 bar, less than the design value (12.45 bar). In conclusion, commissioning results in liquefaction mode match design parameters very well.

4.2. Commissioning of 500W/4.5K refrigerator in Refrigeration mode

The power curve of heater for 500W/4.5K refrigerator in refrigeration mode is shown in figure 5. After the cool-down process finished, the weight of vessel began to increase. The power of heater was increased step by step slowly according the weight curve. When the power increased to 550 W, the weight of vessel was invariant for 30 minutes. This commissioning indicated that the refrigerator can provide 500W refrigeration capacity at 4.5K.
During the steady phase in refrigeration mode, the discharge pressure of the compressor was 11 bar, the mass-flow of the compressor was 86.36 g/s. Electric power was 265.5 kW and the consumption of LN2 was about 12.5/s (or equal power is about 8.79 kW). Therefore, FOM of 500W/4.5K refrigerator in liquefaction mode was 13.2%.

Compared with the design parameters, the mass flow of the compressor was more than the design value (78.84 g/s) by 7.5 g/s. The mass flow of the turbine stream was 46.8 g/s which was more than the design value (40.4 g/s) by 6.4 g/s. Because the input pressure of turbine was operated at 10.2 bar which was larger than the design value (8.7 bar) by 1.5 bar. The actual temperatures of HX4, HX5 were higher than the design parameters. This indicated the actual NTUs of HX4 and HX5 were smaller than the required values. This resulted that the actual efficiency of 500W/4.5K was a little less than the design value.

5. Conclusion
A 500W/4.5K helium refrigerator for ADS project of CAS has been designed including the functional requirements and process analysis. The balanced design between the refrigerator and its liquefier for equal Carnot work with the same high efficiencies is presented based on the variable discharge pressure of compressor and speeds of turbines. The constraints of components and operation strategies in refrigeration mode and liquefaction mode are described.

Commissioning results in liquefaction mode of 500W/4.5K helium refrigerator indicated that it can provide 5.74 g/s (or 165 L/h) LHe with FOM of 14%. Both of the liquefaction rate and FOM were larger than design parameters which were 5.17 g/s (or 150 L/h) and 13.7%. Commissioning results in refrigeration mode of 500W/4.5K helium refrigerator indicated that it can provide 550 W at 4.5K with FOM of 13.2%. But the FOM was less than design parameters which was 13.9% due to the limits of the last two heat exchangers. In a word, this 500W/4.5K helium refrigerator was a balanced system. It operated with almost equivalent Carnot efficiency as either a liquefier or a refrigerator.

6. References
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