Investigations on thermodynamic characteristics of the novel still with combustion chamber used in a closed-cycle cryogen-free dilution refrigerator

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Abstract. The closed-cycle cryogen-free dilution refrigerator (DR) is one of the most promising cryocooler candidates for achieving continuous cooling below 100 mK. As a key component of DR, the still is used to control the circulation rate and the ratio of ^{3}He-^{4}He gas in the cycle, pre-cool the throttled fluid, and provide the power for the dilution cycle. The ^{3}He-^{4}He gas ratio is a key parameter directly affecting the cycle efficiency. The film burner (FB) is a key component for controlling the gas ratio in the still. Therefore, a novel still is proposed, the annular pore is used to guide the superfluid helium, and an FB is set to connect with a ^{4}He shelter. The comprehensive relationship between several parameters such as ^{3}He molar concentration, still cooling power, still heat exchanger initial parameters and the still temperature is determined. FBs can improve the still cooling power by 5.61% (0.39 mW) compared with orifices when the still is 700 mK. The research results provide a reference for the performance optimization and structural design of the still of DR. It will also provide a guidance for increasing the overall cooling capacity of DRs.

1. Introduction

The closed-cycle cryogen-free DR is one of the most promising refrigeration systems capable of achieving continuous cooling below 100 mK. Its electromagnetic interference-free characteristic makes it highly valuable for application in superconducting quantum computing, as it can meet the strict requirements for environmental thermal noise [1], thereby ensureing the stable operation of qubits [2]. Additionally, dilution refrigeration technology is also widely used in deep space exploration [3] and the construction of extreme experimental conditions [4]. The development of DR has undergone an evolution from open to closed cycle, from wet to dry, and from ground to space applications. Currently, closed-cycle cryogen-free DR is the mainstream of dilution refrigeration technology.

As shown in Figure 1, DR mainly consists of a precooling unit, a dilution unit, and a pump unit. In its operating cycle, the compressed ^{3}He gas flows through the precooling refrigerator and the continuous heat exchanger (CHEX) for preliminary cooling. Then, it is decompressed at the JT

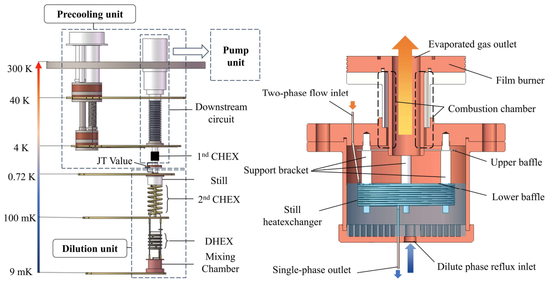

Figure 1. Overall schematic diagram of the dilution refrigeration system and still (right).

valve, completely liquefied through the still heat exchanger, and cooled through CHEX and the discrete heat exchanger (DHEX). After entering the mixing chamber, phase separation occurs, forming a layered structure where pure ^{3}He, the concentrated phase, floats on top, while the dilute solution with low ^{3}He concentration settles at the bottom, called the dilute phase [5]. The dilute phase is subsequently extracted from the mixing chamber and returned to the still. In the still, the ^{3}He-^{4}He mixture evaporates under the combined influence of the heating of the still heater and the decompression of the pump assembly. The mixture is then compressed by the pump unit to enter the next cycle.

The still, a crucial component of the dilution unit, controls the circulation rate and the ^{3}He molar concentration in the circulation. It precools the mixed streams and provides the driving force for the dilution cycle. The ^{3}He molar concentration is a key parameter that directly impacts the cycle efficiency; the higher ^{3}He concentrations result in lower final temperatures and batter system stability. Inside the still, the FB plays a vital role in regulating the gas ratio between ^{3}He and ^{4}He, increasing the ^{3}He molar concentration in the circulating gas through the combustion process of the superfluid helium film.

Previous studies on still [6–8] have confirmed that the presence of internal structures, such as still heaters and FBs, can effectively control the evaporation rate and the ^{3}He molar concentration involved in the cycle. However, some of these structures are relatively complex and the coupling mechanisms between parameters such as the temperature and ^{3}He molar concentration has not been clarified. This paper investigates the detailed design principles and characteristics of the internal structure of the still, focusing on the theoretical exposition of the FB components. A novel still structure for DR used in superconducting quantum computing is proposed. The structure includes a combustion chamber orifice with a smooth electroplated wall and an externally wound heater for the FB. Inside the still, baffles effectively control the internal volume of the chamber, realize the positioning of the still heat exchanger, and block and condens the return flow of ^{4}He gas. Additionally, the influence of different still inlet parameters on the overall cooling capacity of the still under ideal conditions was calculated.

2. Still

In still, the upper baffle is used to prevent ^{4}He gas from directly entering the low-pressure loop, while the lower baffle acts as a positioning baffle, controlling the height of the still heat exchanger coil. The segmented design of the support rod structure effectively defines the positions of the two baffles. The upper end of the still features a sleeve structure, with the interstitial annular space serving as the film combustion chamber, designed to inhibit the ascent of the ^{4}He superfluid film. The rigid outer sleeve endows the entire structure with a certain degree of strength.

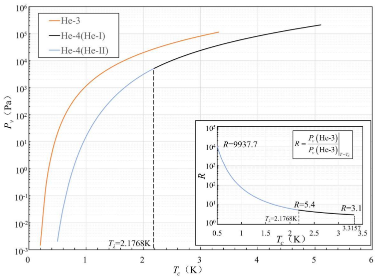

Figure 2. Trends of the saturation vapor pressures of ^{3}He and ^{4}He with temperature. [10]

2.1 Evaporation Process Gas Components

The liquid phase components in the still consist of the ^{3}He-^{4}He mixture, with the ^{4}He component comprising approximately 95%. The gas phase is the ^{3}He-^{4}He mixture, whose composition varies with the temperature inside the still. Typically, at a temperature around 0.7 K in the still, the ^{3}He component proportion exceeds 90%. The pressure inside the still is denoted as

$$P_s = P_3 + P_4 \tag{1}$$

where P_3 is the partial pressure of ^{3}He, and P_4 is the partial pressure of ^{4}He. Vvedenskii et al. [9] proposed that there is a specific relationship between the mole fraction X_3 of ^{3}He in the liquid phase and its partial pressure P_3 as well as the partial pressure P_4 of ^{4}He in the gas phase:

$$P_4 = P_4^0\left(1 - X_3\right) \tag{2}$$

$$P_3 = aP_3^0 X_3 \tag{3}$$

where P_4^0 and P_3^0 represent the vapor pressures of pure isotopes ^{4}He and ^{3}He, respectively. T_s is the temperature of the still. a=4.75(1/ T_s)-0.7. In Figure 2, the saturation vapor pressures of ^{3}He and ^{4}He and their pressure ratio R vary with temperature. At the corresponding temperature within the still, R remains in the order of 10^2. For the still, X_3 is typically within the range of 0.01 to 0.1, and T_s is usually around 0.7 K.

2.2 Superfluid helium film and FB

The temperature in the still is generally below the lambda point of ^{4}He (2.1768 K), so the liquid ^{4}He inside the chamber is in a superfluid state, exhibiting anti-gravity climbing characteristics. Without the FB, the superfluid helium film will climb to the pump path and eventually evaporate due to the rising temperature. The FB can address this issue. Fokkens et al. [11] found that whether the superfluid helium film exhibits superfluid properties is related to the pressure ratio α between its current pressure and the saturation vapor pressure, where $\alpha=P/P_0$. When the pressure ratio α is below the critical pressure ratio, the film is considered to be in a non-superfluid state, thus preventing phenomena like anti-gravity climbing. Therefore, by controlling the pressure inside the still and the temperature at the film's location, it is possible to control α and suppress the superfluid helium film. When it transitions to a superheated fluid, the superfluid helium film evaporates due to heating within the cavity, ultimately achieving the film combustion effect. In ideal conditions, if the heating power of the FB is properly controlled, it can fully suppress the ^{4}He film. The thermodynamic equilibrium within the FB is as follows:

$$\dot{Q} = \left(L + TS\right)\dot{m} = TS_g\dot{m} \tag{4}$$

where Q represents the heat of the FB, L is the latent heat of evaporation, T is the temperature inside the still, TS is the thermodynamic term, is the entropy of the gas, and M is the mass flow rate corresponding to the film. The maximum flow rate of the superfluid helium film is limited by its critical velocity, which is expressed as:

$$\dot{m}_c = 2\pi r v_c d\rho_s \tag{5}$$

where r is the equivalent radius of the space where the film is located, d is the thickness of the superfluid helium film, ρ_s is the density, and v_c is the critical superflow velocity of the film. This allows us to derive the relationship between the heating power of the FB and the critical velocity of the superfluid helium film under ideal conditions. It is important to note that the critical velocity of superfluid helium is generally greater than its actual flow velocity and is influenced by the effective liquid film thickness [12]. It is commonly believed that when the temperature of the film is below 1.3 K, and the thickness is between 2 and 35 nm, the critical velocity v_c of the superfluid helium film is inversely proportional to the film thickness d [13]: $v_c d$=1.23×10^{-4} cm^2/s.

2.3 Cooling power of the still

For the still, the main parameters include the temperature T_s, the evaporation pressure P_s, and the molar concentration of ^{3}He, x, involved in the cycle. These parameters affect the cooling power w of the still, the evaporation rate, and the performance of the DR. In steady-state conditions, the evaporation rate can be considered equal to the system mass flow rate. The cooling power includes the heater power Q and the net cooling power. Considering the heat losses in the still, the overall heat balance can be expressed as follows:

$$W + nx\left(h_{c-3in} - h_{c-3out}\right) + n\left(1-x\right)\left(h_{c-4in} - h_{c-4out}\right) = X_3 nh_3 + \left(1-X_3\right)nh_4 + nxh_{c-3} + n\left(1-x\right)h_{c-4} \tag{8}$$

where h$_c$ represents the enthalpy of the concentrated phase, and n is the mass flow rate. The subscripts in and out denote the inlet and outlet, while the subscripts 3 and 4 correspond to ^{3}He and ^{4}He. Under ideal conditions, where x=1, the heat balance equation can be simplified to:

$$W + n\left(h_{c-3in} - h_{c-3out}\right) = X_3 nh_3 + \left(1-X_3\right)nh_4 + nh_{c-3} \tag{9}$$

It is important to note that the still heat exchanger inlet is in a two-phase state, necessitating consideration of both the single-phase and phase change enthalpy. For simplification, a gas-liquid ratio coefficient can be introduced to ignore the interactions between the two phases. The following results are based on a liquid molar fraction of 0.9 [14].

3. Results and discussion

3.1 Impact of still temperature and X_3 on still pressure

As shown in Figure 3, under the same still temperature conditions, the pressure in the still increases with the ^{3}He molar fraction. The pressure in the still is macroscopically controlled by the still heater and the pump group [15]. When the pressure rises, the requirements for pressure drop along the pump path decrease, and the pump group’s pumping rate requirements are reduced. Therefore, a higher molar fraction of liquid ^{3}He in the still is more favorable for the stable circulation of the dilution refrigeration system. Similarly, under the same ^{3}He molar fraction conditions, the corresponding pressure in the chamber also rises gradually when the still temperature increases. This trend resembles the increase in ^{3}He and ^{4}He saturation vapor pressure with rising temperature.

3.2 Temperature settings for the FB

Based on the results from the previous section, for a still temperature of 0.7 K and a liquid ^{3}He molar fraction of 0.06, the pressure within the still is 64.78 Pa. To simplify calculations, we assume that the pressure inside the still remains stable and is not affected by the heating power of the FB.

As shown in Figure 4, for a still temperature of 0.7 K, the ratio of the still pressure to the ^{4}He saturation vapor pressure varies with temperature for different ^{3}He molar fractions, intersecting with the critical pressure ratio at different points. As the still pressure decreases, the intersection temperature value also decreases. Under ideal conditions, when the FB temperature exceeds the intersection temperature, the superfluid helium film will transition to a superheated liquid state and evaporate upon heating. Thus, a dynamic equilibrium can be achieved in the film combustion chamber when the effective heating power Q of the FB equals the power required to combust the superfluid helium film.

3.3 Cooling power of the still

As shown in Figure 5, with the still temperature held constant, a higher temperature of the two-phase flow at the still inlet results in a lower cooling power. Conversely, with constant inlet

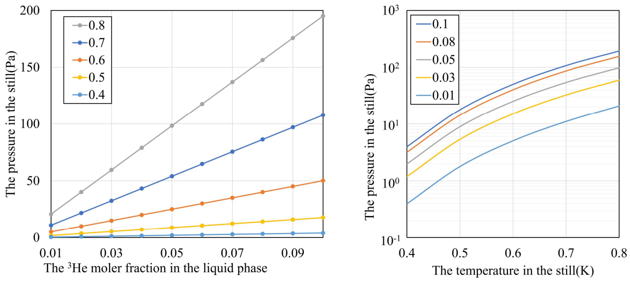

Figure 3. Schematic diagram of the effect of temperature and X3 on pressure in the still.

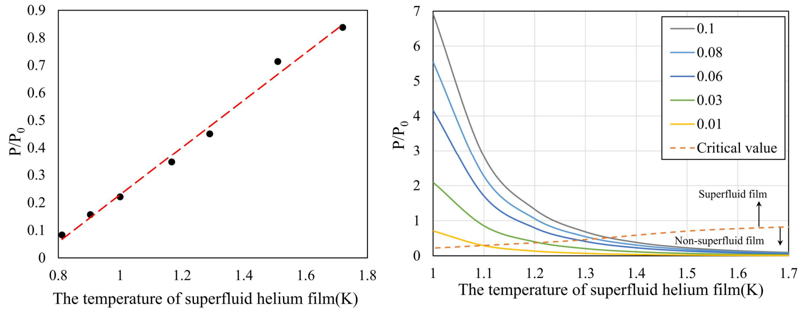

Figure 4. Fitting relationship between the critical pressure ratio to sustain thin film superfluidity and temperature [10], temperature settings for FB.

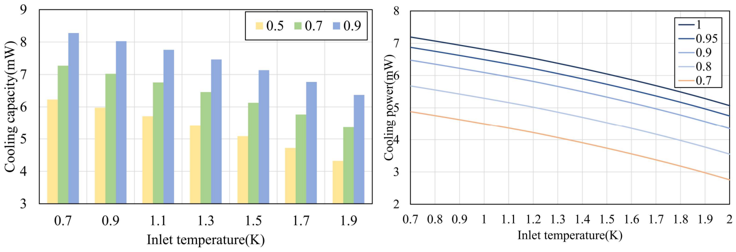

Figure 5. Variation trends of still cooling power with still temperature and ^{3}He molar concentration.

parameters, a higher still temperature increases the cooling power, aligning with the properties ^{3}He. In non-ideal conditions, considering the effect of ^{3}He molar concentration at the still outlet, the cooling power decreases when the ^{3}He molar concentration decreases. In some DRs, orifices are used to suppress the superfluid helium film. Under this method, the ^{3}He moler fraction extreme value of the outlet gas of the still is about 95% [16]. When the film burner is used, this value is 99.84% in an ideal state. The still cooling power is increased by 5.61% (0.39 mW) when the still is 700 mK.

4. Conclusions

This paper analyzes the relationship in the still between pressure, temperature, and ^{3}He molar concentration in the dilute phase. The relationship between the heating power of FB and film flow is established. Based on the enthalpy analysis, the relationship between the total still cooling power and parameters such as still temperature, ^{3}He molar fraction in the dilute phase, and outlet ^{3}He molar fraction is established. The results shows that when the heating power of the FB at a given temperature equals the power required for the evaporation of the superfluid helium film, the design proposed in this paper can theoretically achieve a certain degree of superfluid helium film suppression. Considering the effects of still pressure, FB heating power, and inlet parameters, an optimal still temperature exists. Compared with the orifice, the FB can improve the still cooling power by 5.61% (0.39 mW) when the still is 700 mK, which provides helpful guidance for improving the overall cooling capacity of DR.

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