Study on the multiple cooling output characteristics of a gas-coupled high-frequency pulse tube cryocooler

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Abstract. Gas-coupled type multi-stage high-frequency pulse tube cryocoolers (HPTCs) whose different stages are coupled directly through mass flow offer unique advantages in terms of compact structure and small volume and weight, leading to significant application prospects in special fields such as deep space exploration. However, limited by the subtle intrinsic interaction of gas proportion and energy flow among different stages, few studies have been carried out on the mass-energy transfer mechanism of such cryocooler at cryogenic temperatures below liquid hydrogen, where the cooling capacities can be inevitably small compared to low-frequency cryocoolers. Furthermore, the cooling output is usually feasible only at the cold end of each stage. In order to optimize the refrigeration process of the gas-coupled type HPTCs and to improve the utilization efficiency of the cooling capacities in the higher temperature zone along the cryocooler, a pre-cooling type two-stage gas-coupled HPTC working at liquid-helium temperatures was designed to achieve stepped cooling output. The inter-stage multiple cooling output characteristics and the intra-stage cooling extraction mechanism were investigated. The research results can provide a useful reference for the practical application of a single HPTC with simultaneous multiple cooling output at different cryogenic temperatures.

1. Introduction

In order to obtain liquid hydrogen, liquid helium, or even extremely-low mK temperatures, the refrigeration system usually needs to be cooled in stages, thus requiring multiple cryocoolers operating in different temperature ranges to provide cooling separately. For example, an adiabatic demagnetization refrigerator (ADR) working at mK temperature requires not only a 4 K cryocooler as a pre-cooling stage, but often additional radiant cooling screens working in the liquid nitrogen and liquid hydrogen temperature ranges to reduce heat leakage from room temperature to cryogenic temperatures, which require additional cryocoolers to provide stepped cooling [1]. For special applications such as space applications, refrigeration systems consisting of multiple cryocoolers operating in different temperature ranges are challenging to optimize in terms of size and weight. Therefore, the use of a single cryocooler to provide multiple cooling will be advantageous. Among them, the high-frequency pulse tube cryocooler (HPTC) [2] operating at a high frequency usually above 20 Hz gives it the advantages of high compactness and low volume and weight, which is a potentially important solution for the development of multi-temperature range cooling with a single cryocooler.

In multi-stage HPTCs, the thermally-coupled structure in which all stages are connected through thermal bridges is intuitive and the cooling output of each stage is not affected by each other, while the gas-coupled structure in which the gas and energy flows between the stages are coupled to each other is more compact, and thus has received extensive attention from researchers [3,4]. However, there is still a lack of research on multiple cooling output for such structure. Therefore, a pre-cooling type two-stage gas-coupled HPTC was designed in this paper, and the inter-stage multiple cooling output characteristics of the gas-coupled stages were investigated through a whole cryocooler model, so as to clarify the intrinsic connection of the cooling outputs of gas-coupled different stages. In addition, in order to enhance the cooling output capacity of the low-temperature stage, the cooling output characteristics within the low-temperature stage regenerator were investigated to achieve the simultaneous multiple cooling outputs at the cold end and the intra-stage of the single-stage regenerator. The results of this study can provide a useful reference for the practical application of a single cryocooler with multiple cooling outputs.

2. Cryocooler structure

Figure 1 shows the design of a pre-cooling type two-stage gas-coupled HPTC, in which the temperature of the hot end of the gas-coupled first stage is reduced as much as possible by a pre-cooling stage in order to obtain the liquid-helium temperature at the cold end of the gas-coupled second stage. Among them, the pre-cooling stage can adopt a single-stage HPTC to flexibly adjust the pre-cooling temperature. The gas-coupled two-stage adopts the coaxial structure to improve the compactness of the cold finger, while both stages use the multi-structure joint phase shifting method including the double inlet and inertance tube to enhance the phase shifting capability.

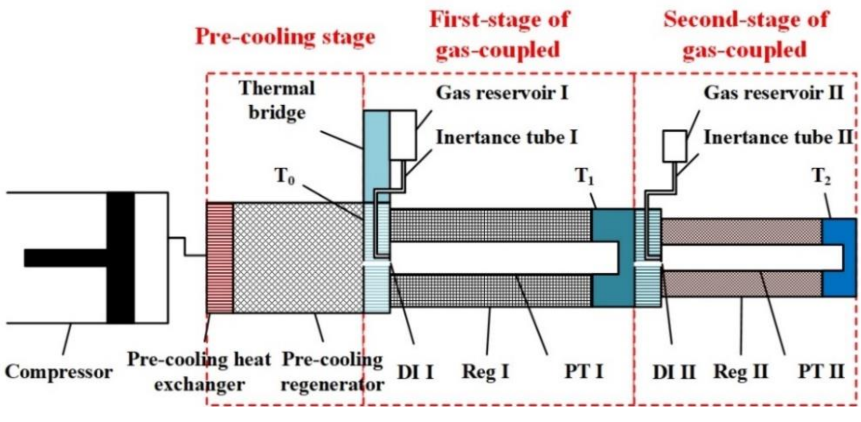

Figure 1. Structure of the pre-cooling type two-stage gas-coupled HPTC.

For this cryocooler, apart from the pre-cooling stage, only two domains of cooling outputs in the liquid-hydrogen and liquid-helium temperature ranges, are normally available at the cold end of the gas-coupled two stages. Due to the uniqueness of the gas-coupled structure, there is a subtle connection between the energy flows in these two regenerators, which is intuitively different from that of the thermally-coupled structure where the cooling output of the two stages are independent of each other. Thus, the focus of this paper is to clarify the cooling output characteristics of the gas-coupled structure. In addition, in order to improve the cooling output capacity, this paper will explore additional cooling output apart from the cold end in the working temperature range of the non-ideal gas effect. The effect of cooling output in the intra-stage of the gas-coupled structure on the refrigeration performance of the various stages will be the key target.

3. Analysis of multiple cooling output mechanism

3.1 Simulation model

Based on Sage, a simulation calculation model of the cryocooler shown in Figure 2 was constructed, and the inter-stage and intra-stage cooling output characteristics were analyzed respectively. It is worth noting that in order to avoid the low-temperature gas in the pre-cooling stage directly into the compressor to affect its performance, the pre-cooling stage adopts a regenerator as the transition to establish a temperature gradient. The key parameters of the model are shown in Table 1, where each diameter parameter refers to the inner diameter. Stainless steel wire meshes, Er_3Ni and $HoCu_2$ spheres were chosen as the regenerator materials for different stages, respectively.

Table 1. Parameters of Sage model.

Parameter	Value
Working fluid	Helium-4
Pressure	1.35 MPa
Frequency	26.5 Hz
Pre-cooling regenerator	φ18×43 mm
Gas-coupled first-stage regenerator	φ18×60 mm
Gas-coupled first-stage pulse tube	φ8.5×70 mm
Gas-coupled second-stage regenerator	φ14.2×65 mm
Gas-coupled second-stage pulse tube	φ6.3×75 mm

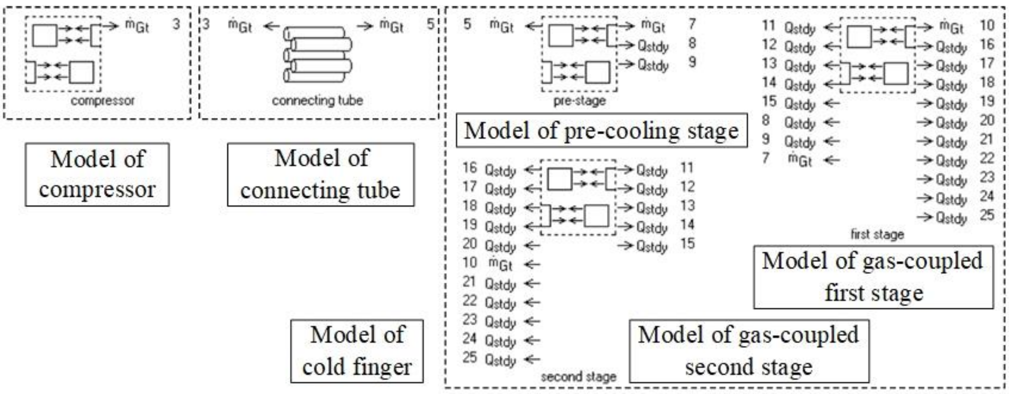

Figure 2. Model of the pre-cooling type HPTC based on Sage.

3.2 Inter-stage cooling output characteristics

Firstly, based on the above model, the cooling output characteristics between the gas-coupled stages can be analyzed. The interaction mechanism of the refrigeration performance of the two stages is explored by studying the effect of cooling output at the cold end of the two stages respectively on the refrigeration performance of the other stage. From the simulation results shown in Figure 3, it can be seen that the cold end temperature of the first stage increases significantly with cooling outputs, but hardly affects the cold end temperature of the second stage. And with cooling outputs of the second stage, its temperature increases significantly, while the temperature of the first cold end is almost unaffected. It is clear that the cooling output of the gas-coupled two-stage structure designed in this paper hardly interferes with each other, and the cooling power of the two different stages can be output independently, which is similar to the thermally-coupled structure.

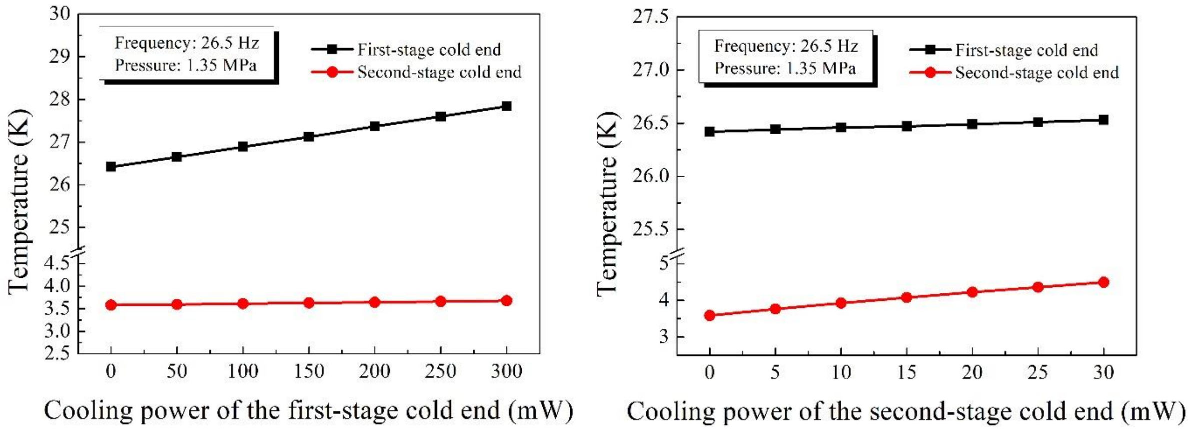

Figure 3. Effect of getting cooling powers at the first-stage (left) and second-stage (right) cold end on two-stage cooling temperatures.

The intrinsic mechanism by which the gas-coupled two-stage cooling capacities can be output independently is driven by the non-ideal gas effect. As shown in equation (1), the energy flow at any location within the regenerator $\langle \dot{E} \rangle_x$ can be expressed as a function of temperature T_m and temperature gradient $\frac{dT_m}{dx}$, where $\langle P\dot{V} \rangle$ represents the PV power in the regenerator, φ represents the porosity of the regenerator, and f_s represents the thermal conduction factor of the regenerator materials [5-7].

$$\langle \dot{E} \rangle_x = (1 - T_m\alpha_v)\langle P\dot{V} \rangle + \frac{\epsilon_s + \sigma(1+\epsilon_s)}{(1+\sigma)(1+\epsilon_s)} T_m\alpha_v \langle P\dot{V} \rangle$$
$$+ \frac{\rho_m c_p}{2\omega\varphi A(1-\sigma)|1-f_v|^2} Im\left[f_v^* + \frac{(1-f_v^*)(1+\epsilon_s f_v)}{(1+\sigma)(1+\epsilon_s)} \right] \left| \widehat{U}_1 \right|^2 \frac{dT_m}{dx}$$
$$- f_s(1-\varphi)Ak_s \frac{dT_m}{dx} \quad (1)$$

At the cold end of the second-stage regenerator, due to the sharp increase in pressure-induced enthalpy, the temperature gradient will become very small or even approach zero when the total energy flow keeps constant, and the energy flow at the cold end $\langle \dot{E} \rangle_c$ will be almost a function of the temperature T_c:

$$\langle \dot{E} \rangle_c \approx \left(1 - T_c\alpha_{v,c}\right)\langle P\dot{V} \rangle_c + \frac{\epsilon_s + \sigma(1+\epsilon_s)}{(1+\sigma)(1+\epsilon_s)} T_c\alpha_{v,c}\langle P\dot{V} \rangle_c \quad (2)$$

Thus, the cooling power at the cold end $\dot{Q}_c$ can be obtained according to:

$$\dot{Q}_c = \langle P\dot{V}\rangle_c - \langle \dot{E}\rangle_c \approx \frac{1}{(1+\sigma)(1+\epsilon_s)} T_c \alpha_{v,c} \langle P\dot{V}\rangle_c \tag{3}$$

At the hot end of the regenerator, the non-ideal gas effect of the working fluid is significantly weakened, while the specific heat of the regenerator material is significantly increased, and the energy flow at the hot end $\langle \dot{E}\rangle_h$ at this time can be expressed by equation (4). It can be seen that, different from the cold end, the energy flow at the hot end of the stage is controlled by the temperature gradient $\frac{dT_m}{dx}$ and is independent of the temperature.

$$\langle \dot{E}\rangle_h \approx \frac{\sigma}{1+\sigma}\langle P\dot{V}\rangle_h + \frac{\rho_m c_p}{2\omega\varphi A(1-\sigma)|1-f_v|^2} Im\left[f_v^* + \frac{1-f_v^*}{1+\sigma}\right]\left|\hat{U}_1\right|^2 \frac{dT_m}{dx} - f_s(1-\varphi)Ak_s\frac{dT_m}{dx} \tag{4}$$

From the temperature distribution of the second-stage regenerator shown in Figure 4, it can be seen that when the cooling output occurs at the first cold end, only the temperature distribution of the second-stage regenerator close to the hot end has been changed and hardly affects the temperature distribution of its cold end. As the temperature gradient remains zero for a long distance near the cold end, the non-ideal gas effect of the cold-end gas does not decay at this time, and the temperature-controlled energy flow remains unchanged. Thus, its refrigeration performance keeps almost unchanged with the cooling output of the first stage. Furthermore, since the PV work at the cold end of the second regenerator remains almost constant, the cooling output from the first-stage cold end can be eventually realized at the expense of a reduction in the equivalent enthalpy flow.

Correspondingly, the near-zero temperature gradient due to the non-ideal gas effect remains almost constant when the cooling output at the second-stage cold end is cancelled out locally in the form of an additional energy flow. In addition, the energy flow controlled by the temperature gradient remains unchanged because the cooling output at the second-stage cold end hardly affects the temperature distribution near the first-stage cold end. At the same time, the PV work at the first-stage cold end also remains unchanged, so the refrigeration performance of the first-stage cold end is also almost unaffected by the cooling output of the second-stage cold end.

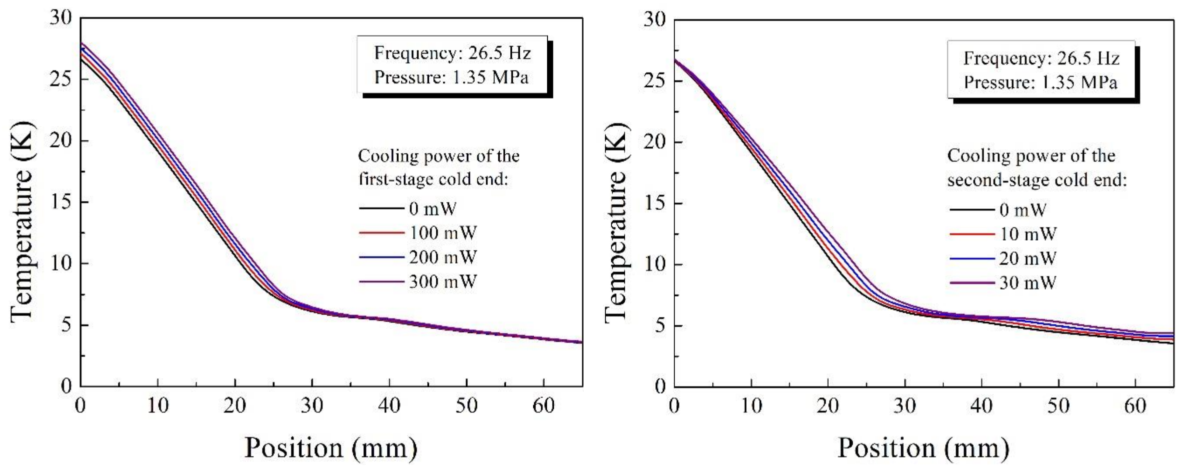

Figure 4. Effect of getting cooling powers at the first-stage (left) and second-stage (right) cold end on axial temperature distribution of the second-stage regenerator.

3.3 Intra-stage cooling output characteristics

In addition to the cooling output at the cold end of the gas-coupled two stages, this paper further explores the cooling output characteristics in the mid-region of the gas-coupled second stage, that is, the cooling output characteristics of the intra-stage. Different from the inter-stage cooling output, the intra-stage cooling output will directly change the local energy flow distribution. In this paper, the effect on the two-stage cooling performance is investigated by fixing the temperature of the second-stage cold end at 4 K and outputting different cooling powers at the 1/4 position of the second stage regenerator (near the hot end). As shown in Figure 5, the cooling power of the cold end remains basically unchanged when 0~200 mW of cooling power is output in the inter-stage of the regenerator (which can be referred to as "free cooling power"), while it decreases significantly after continuing to increase the cooling output. Next, the intrinsic factors will be investigated in detail from the temperature distribution and energy flow characteristics in the cryocooler.

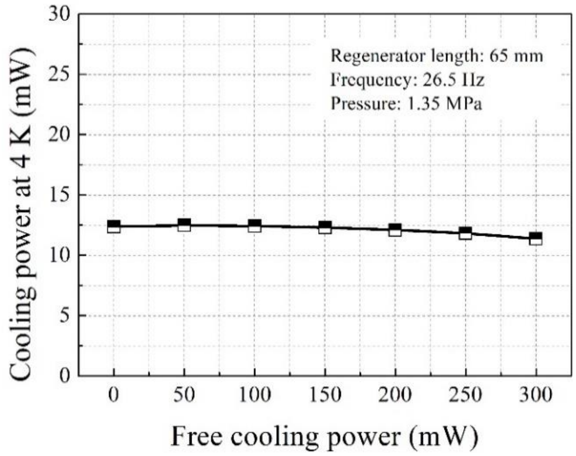

Figure 5. Effect of free cooling power on cooling power of the second-stage cold end.

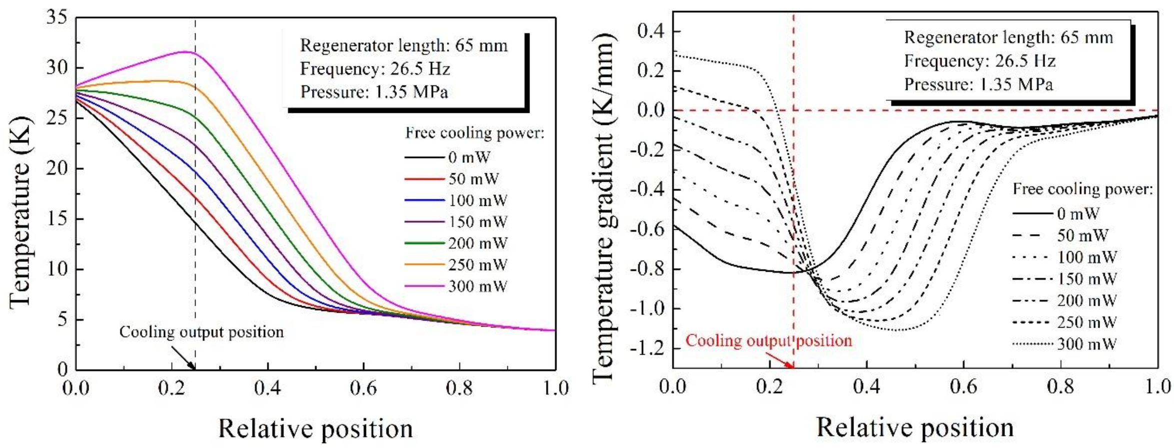

Figure 6. Effect of free cooling power on axial temperature (left) and temperature gradient (right) distribution.

As shown in Figure 6, the temperature distribution along the regenerator changes significantly after the cooling output in the intra-stage: the temperature increases significantly at the outputting position, while the temperature near the cold end hardly changes. From the temperature gradient distribution, it can also be seen that in the upstream of the cooling output position (near the hot end of the regenerator), the absolute value of the temperature gradient decreases significantly or even reverses with the increase of the cooling output, while in the downstream of the cooling output position, the absolute value of the temperature gradient increases significantly with the increase of the cooling output. However, close to the cold end, the temperature gradient controlled by the non-ideal gas effect hardly changes, which is the fundamental reason why the regenerator can realize the additional cooling output in the intra-stage without affecting the cooling power at the cold end.

The mechanism of cooling output in the intra-stage can be analyzed in terms of the energy flow characteristics. From the law of conservation of energy, it can be seen that when the cooling power is output in the intra-stage, the energy flow downstream of the output location remains unchanged due to the near-zero temperature gradient close to the cold end, while the energy flow upstream changes significantly:

$$\dot{Q}_{free} = \langle \dot{E} \rangle_h - \langle \dot{E} \rangle'_h = \Delta \langle \dot{E} \rangle_h \quad (5)$$

It can be seen that the cooling output in the intra-stage is the reduction of the energy flow at the hot end, which is achieved by changing the temperature gradient at the hot end. The greater the temperature gradient at the hot end, the larger the cooing output in the intra-stage.

From Figure 7, it is clear that when the cooling output in the intra-stage is less than 200 mW, the non-ideal gas effect shields the interference of the energy flow in the cold end from the cooling extraction in the intra-stage. The cooling output is transferred to the hot end in the form of additional energy flow, which ultimately results in a decrease in the equivalent enthalpy flow, and as a result, the temperature of the first-stage cold end increases, along with a decrease in its refrigeration performance. When the cooling output from the intra-stage exceeds 200 mW, the output is split into two parts in the form of energy flows to the hot and cold ends: the energy flow to the hot end reduces the enthalpy flow near the hot end, and the additional energy flow to the cold end increases the local energy flow, thus reducing the cooling power.

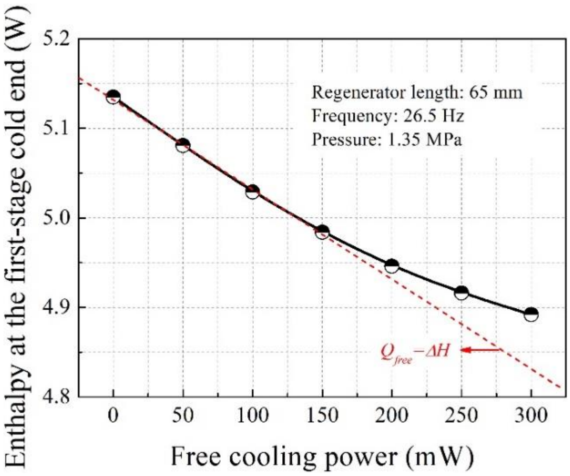

Figure 7. Effect of free cooling power on enthalpy at the first-stage cold end.

4. Conclusions

A pre-cooling type two-stage gas-coupled high-frequency pulse tube cryocooler has been designed to realize multiple cooling outputs from a single cryocooler. Numerical calculations of the whole cryocooler found that: when the first and second cold ends respectively output the appropriate cold power, it will hardly affect the refrigeration performance of the other stage, which is conducive to the stepped utilization of cooling powers in different temperature regions. At the same time, under the non-ideal gas effect, it is feasible to output suitable cooling powers in the intra-stage of the second-stage regenerator at the expense of reducing the cooling power of the first-stage cold end, with near-zero impact on the cooling power of the second-stage cold end. However, when the cooling output is too large, the refrigeration performance of both stages will be reduced. The research results of this paper can provide a useful reference for a single cryocooler to simultaneously output multiple cooling powers, and can also guide the practical application of cooling output in the intra-stage of a high-frequency pulse tube cryocooler with small cooling powers.

Acknowledgments

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