

Theoretical Analyses and Design of a 4 K Gas-Coupled Multi-Bypass Stirling-Type Pulse Tube Cryocooler

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Abstract: Gas-coupled Stirling-type pulse tube cryocooler (SPTC) is currently the most compact and simplest configuration among all types of cryocoolers, but it is challenging to achieve a very low temperature. This paper investigates a gas-coupled SPTC which is capable of directly achieving a temperature of around 4 K. Theoretical analyses were performed based on SAGE to study the effects of employing one or more multi-bypass structures on apparent cooling performance, and internal working parameters. The simulation results indicate that the function of the multi-bypass is similar to that of a multi-stage gas-coupled structure, producing a pre-cooling effect on the lower-temperature section by increasing the acoustic power and the enthalpy flow in the pulse tube of the higher-temperature section. The cooperation of two multi-bypass structures can promote a higher enhancement of the cooling performance, but it is difficult to achieve the same cooling performance of a completely multi-stage gas-coupled SPTC due to weak phase-shifting capability and excessive reduction of the mass flow. Based on the model, the developed prototype has achieved a no-load temperature of 4.4 K, which shows the great potential of using a gas-coupled SPTC to obtain a cooling temperature below 4 K.

Keywords: gas-coupled, multi-bypass, stirling-type, pulse tube, cryocooler

1. Introduction

Pulse tube cryocooler (PTC), a kind of small-sized regenerative refrigerators, has been widely acknowledged as a significant technological innovation in the field of cryogenic engineering because it completely eliminates moving parts in the cold finger, which endows it with significant advantages in terms of low vibration and high reliability [1–3]. Stirling-type pulse tube cryocooler (SPTC) driven by the non-oil-lubrication dual-opposed linear compressor employing the well-proven flexure springs and clearance technology further realizes high

compactness and good stability, which thus makes it an attractive and preferred choice to provide the mandatory low-temperature environment for some special fields, especially in space [4–6]. Contemporary deep space exploration missions raise new requirements and challenges for the existing SPTCs [7–9]. Achieving a lower cooling temperature based on a more compact structure has become one of the long-standing goals in current space applications [10].

Most of SPTCs that have been reported to achieve an effective cooling capacity at 10 K or below are two-stage or more-stage structures [11–15]. Generally, there are

two typical inter-stage arrangements for multi-stage SPTCs, namely, the thermal-coupled and the gas-coupled. Specifically, Dang et al. used a thermal-coupled four-stage structure and achieved a no-load temperature of 4.2 K with He-4 or a no-load temperature of 3.3 K with He-3 [11, 12]. Wu et al. used a gas-coupled two-stage structure and obtained a no-load temperature of 5.7 K with He-4 [13]. Additionally, some multi-stage SPTCs might also adopt the mixed coupling approach, in which the former stages are thermal-coupled while the latter stages are gas-coupled, and vice versa. Chen et al. developed a similar three-stage structure and achieved a no-load temperature of 3.6 K with He-4 [14, 15]. Compared to the thermal-coupled and the mixed coupling approach, the completely gas-coupled SPTC is driven by a single compressor and is more similar to a single-stage SPTC from the outside appearance without any thermal links, which endows it with a more compact structure and higher-potential efficiency [10, 13]. However, the gas-coupled SPTC is much more difficult to design and optimize because the charge pressure and especially the operating frequency have to be kept the same for each stage, and minor modifications might change gas distribution characteristics of the whole system, thus resulting in changes of temperature distribution, energy flow distribution, and phase relationship at each stage [10]. Therefore, the completely gas-coupled SPTC is rarely researched and reported, but is still desirable in practical space applications because of its lighter weight, simpler system, and higher efficiency.

With the invention and development of the basic PTC, the orifice PTC and the third generation PTC, such as double-inlet and inertance tube PTC [16–21], the phase shifter has always been crucial for the performance improvement of the PTC. Currently, most of SPTCs working in the lower temperature range employ the coupling phase shifters of inertance tube and double-inlet [13–15, 22–25]. In order to further improve the refrigeration performance of the SPTC, investigations of some novel phase shifter devices have also been carried out on mass-spring (or gas-spring) feedback, step piston, cascade style, etc. [26–30]. In these SPTCs besides a compressor as moving part at room temperature, there is a piston or displacer at the warm end of the pulse tube to recover the expansion work. Though these cryocoolers have achieved higher refrigeration efficiency, it is almost inevitable for more complex cooling systems and delicate mechanical processing. The multi-bypass, also as an innovative phase shifter, retains the original compactness and complexity of the system, whose opening can be adjusted by direct drilling [10, 31–34]. Zhou et al. used a multi-bypass single-stage SPTC and achieved a no-load temperature of 13.9 K, which is basically equivalent to

the performance of a two-stage SPTC [32]. Besides, the multi-bypass also demonstrated prominent advantages for other type cryocoolers. Pan et al. used a Vuilleumier (VM) type multi-bypass PTC and obtained a no-load temperature of 3.7 K with He-4, which is also equivalent to the performance of a two-stage Vuilleumier type pulse tube cryocooler (VPTC) [33]. Different from the low-frequency cryocoolers, employing multi-bypass in SPTCs to achieve such a low temperature is confronted with huge challenges because of larger irreversible heat exchange loss caused by smaller heat penetration depth, and more difficulties of phase-shifting with smaller acoustic power [34]. Till now, the employment of the multi-bypass in multi-stage SPTCs operating at a very low temperature has yet been researched and reported, especially in gas-coupled SPTCs, while its working mechanism is still unclear.

This paper conducted systematic theoretical analyses of a gas-coupled multi-bypass SPTC aimed at directly reaching a temperature of around 4 K. The whole design and optimization process of this cryocooler will be detailedly presented in the following. First, the working mechanism of multi-bypass and double-inlet employed in a single-stage SPTC was numerically studied and compared. Then, the cooperation adjustment of two multi-bypass structures was also simulated and analyzed to further improve the cooling performance. After resolving the main constraint on the enhancement of cooling performance, it became a completely two-stage gas-coupled multi-bypass SPTC by attaching an inertance tube and a reservoir to one of two multi-bypass structures. Through further optimization of structural parameters and matrix materials, the model finally obtained a temperature of around 4 K.

It should be mentioned here that this paper is not just one analysis and design, but the fruit of a long research and development program, and the developed cryocooler prototype has achieved the lowest temperature of 4.4 K [10], which shows the great potential of using a completely gas-coupled SPTC to obtain a cooling temperature below 4 K.

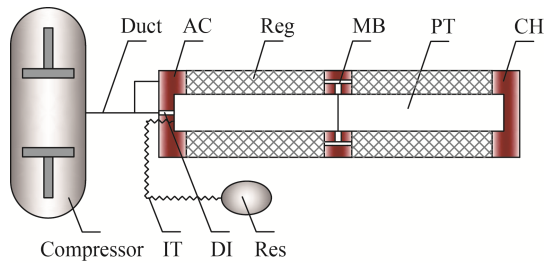
2. Simulation Methods

All calculations in this paper are based on SAGE software [35], which is currently the most widely used in the field of cryocooler research. Compared with other commercial software, SAGE connects model components through mass flow, momentum flow and energy flow that supports simulation and optimization of the whole system, representing a Stirling-cycle machine, a spring-mass-damper resonant system, or anything else that has been properly coded to work with it. SAGE also

uses abundant empirical calibration constants for computing various actual losses from each component. In addition, SAGE extends the pulse-tube model with a special gas type having an equation of state designed for accuracy at extremely low temperatures (near the working gas critical temperature). Although SAGE also makes some assumptions and simplifications, it can still provide valuable guidance on the design and experiment of SPTCs.

3. Comparison of Multi-Bypass and Double-Inlet

The schematic of a typical multi-bypass single-stage SPTC is shown in Fig. 1, where the arrangement of the regenerator and the pulse tube is coaxial to further enhance the compactness. As shown in the figure, compared with the double-inlet where a part of the working gas is introduced or removed by means of a connection between the regenerator inlet and the pulse tube outlet, the multi-bypass achieves a similar function by means of a connection between the middle of the regenerator and the pulse tube. Therefore, from the



AC: aftercooler; Reg: regenerator; PT: pulse tube; CH: cold-end heat exchanger; IT: inertance tube; Res: reservoir; MB: multi-bypass; DI: double-inlet

Fig. 1 Schematic of the multi-bypass single-stage SPTC

Table 1 Parameter details of the single-stage SPTC

Operating parameter	Value
Working gas	He-4
Input electric power	400 W
Input current amplitude	5.5 A
Charge pressure	2.5 MPa
Operating frequency	25 Hz
Structural parameter	Value
Regenerator length/diameter	90 mm/26 mm
Pulse tube length/diameter	107 mm/12 mm
Inertance tube length/diameter	1.4 m/2 mm+3 m/3 mm+4 m/4 mm
Reservoir volume	600 cm ³
Regenerator matrix	Material
Regenerator	304 stainless steel mesh (SS)

outside appearance, the double-inlet is equivalent to the multi-bypass operating in the warm end of the regenerator. In this section, the multi-bypass operating at different positions of the regenerator is simulated, and their working mechanism and impact on the cooling performance are also analyzed and compared. Table 1 gives some optimized parameter details in the calculation.

3.1 Effect of the multi-bypass at different positions on the cooling performance

Fig. 2 shows the variation of the no-load temperature with different openings of the multi-bypass operating at different positions of the regenerator. X represents the relative position of the multi-bypass on the regenerator: $X=0/5$ means the multi-bypass operates at the warm end of the regenerator; i.e., it is a double-inlet. And the $X=5/5$ means the multi-bypass operates at the cold end of the regenerator; i.e., it is just a traditional SPTC. It can be seen from the figure that the effect of the multi-bypass at different positions is quite variable on the performance. Without the multi-bypass or the double-inlet, the no-load temperature of the single-stage SPTC can only reach around 32 K. The double-inlet with an optimal opening can reduce the no-load temperature to 23.5 K. And the multi-bypass with an optimal opening approaching the middle or cold end of the regenerator can further reduce the no-load temperature, which can even decrease to around 17 K. Moreover, as the multi-bypass is employed successively from the warm end to the cold end of the regenerator, its function of improving the performance increases first and then decreases, but the corresponding optimal opening gradually increases.

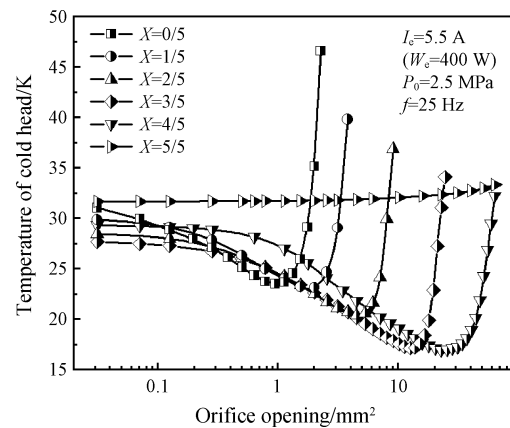


Fig. 2 Impact of multi-bypass opening and position on no-load temperature of the cold head

3.2 Working mechanism comparison of multi-bypass and double-inlet

Double-inlet can improve the cooling performance since it has been shown to increase the acoustic power at

the entrance of the inertance tube and the pressure ratio in the pulse tube [36], which benefits the enhancement of the phase-shifting capability within the warm end of the pulse tube. Fig. 3 shows the variations of the corresponding characteristics with different openings and positions of multi-bypass. It can be seen that while the multi-bypass operates in the middle of the regenerator and the pulse tube, it still has an effect on the characteristics of the outlet of the pulse tube. Moreover, some of the characteristics produced by the double-inlet with an optimal opening can also be generated by

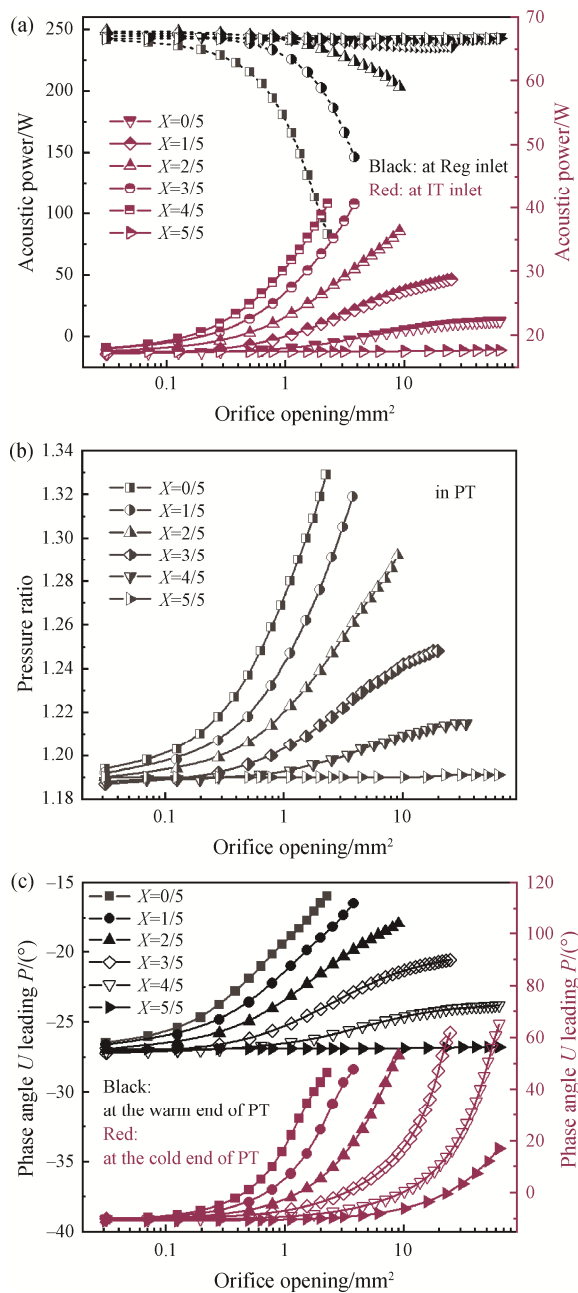


Fig. 3 Impact of multi-bypass opening and position on acoustic power, pressure ratio and phase angle

multi-bypass with a larger optimal opening approaching the middle or cold end of the regenerator. It includes promoting the increase of the acoustic power at the entrance of the inertance tube and the pressure ratio in the pulse tube, and the generation of a suitable phase angle at the warm end of the pulse tube. Additionally, as the opening increases, the multi-bypass near the middle or the cold end of the regenerator stems from the decrease of the acoustic power at the entrance of the regenerator, whose decrease will dramatically weaken the working ability of the gas in the regenerator and the cold head. However, an excessive opening will sharply deteriorate the phase angle of the cold end of the pulse tube, which will adversely worsen the cooling performance.

The cooperation phase adjustment method of the multi-bypass and the double-inlet has shown its advantages in previous experiments, where the direct current introduced by multi-bypass or double-inlet can be interactively suppressed [37]. The above analyses indicate that a single multi-bypass operating at the middle or near the cold end of the regenerator can more effectively improve the cooling performance than a single double-inlet. Therefore, the coupling adjustment of two multi-bypass structures might have a better function than that of the multi-bypass and the double-inlet. The corresponding analyses will be implemented in the following.

4. Cooperation Adjustment of Two Multi-Bypass Structures

The schematic of the single-stage SPTC with two multi-bypass structures is shown in Fig. 4. As shown in the figure, multi-bypass 1 (where $X=1/3$) and multi-bypass 2 (where $X=2/3$) are simultaneously employed in the middle and near the cold end of the regenerator, where the regenerator and other structural parameters remain constant. In this section, the coupling

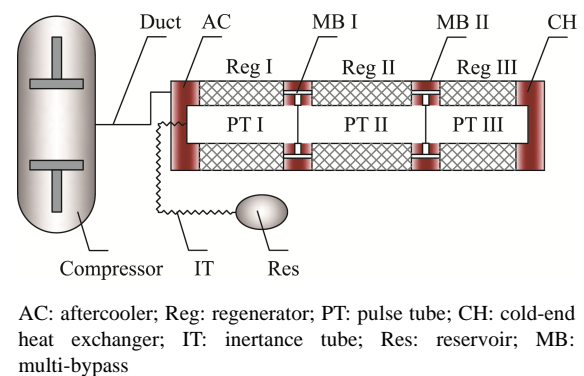


Fig. 4 Schematic of the single-stage SPTC with two multi-bypass structures

adjustment of two multi-bypass structures is simulated, whose effects are also analyzed on the cooling performance and some fundamental physical characteristics along with the regenerator and the pulse tube. The corresponding parameter details in this calculation are completely consistent with those of the single-stage SPTC in Table 1.

4.1 Effect of two multi-bypass structures on the cooling performance

Fig. 5 shows the variation of cooling temperature at the cold head, multi-bypass 1, or multi-bypass 2 with different orifice openings. It can be seen that the cooperation adjustment of two multi-bypass structures can further improve the cooling performance. Specifically, when only multi-bypass 2 is employed with an optimal opening, the single-stage SPTC can obtain a no-load temperature of around 17 K. The corresponding temperature can be further reduced to 13.4 K when multi-bypass 1 is also employed simultaneously with an optimal opening. Moreover, as the orifice opening increases, the temperature of multi-bypass 1 or multi-bypass 2 significantly drops, which indicates multi-bypass might produce a pre-cooling effect at the employment position.

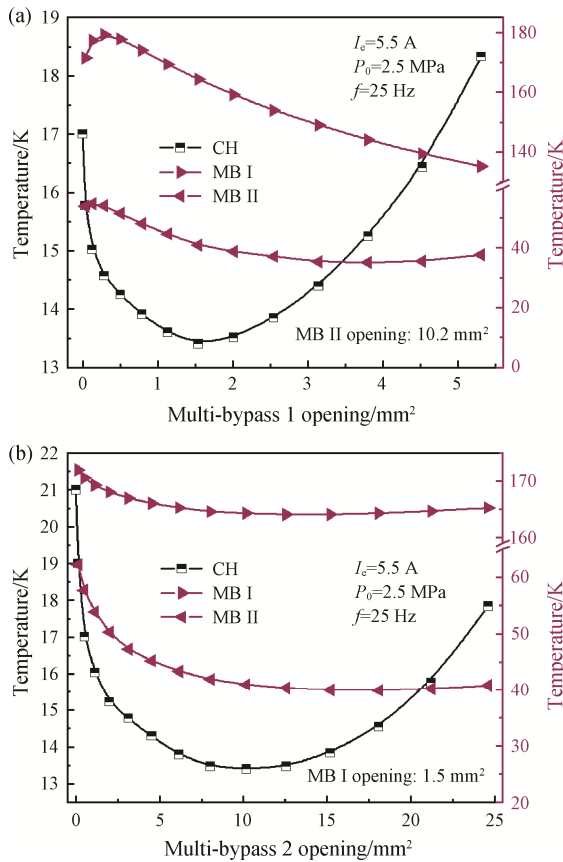


Fig. 5 Impact of two multi-bypass structures on the cooling temperature

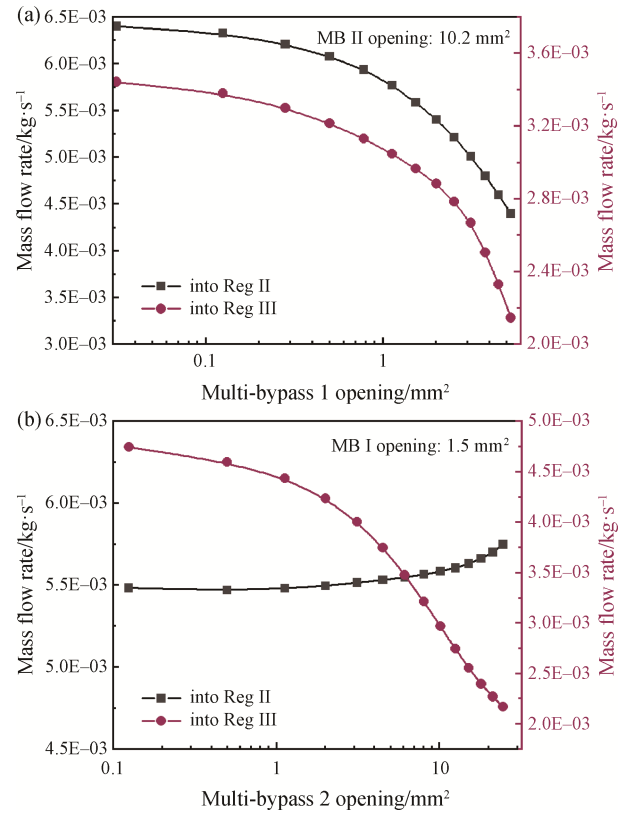


Fig. 6 Impact of two multi-bypass structures on the mass flow of the working gas

Gas distribution characteristics is an important issue in the research of gas-coupled SPTCs. Fig. 6 shows the variation of the mass flow rate of the working gas entering regenerator 2 or regenerator 3 with multi-bypass 1 or multi-bypass 2. As shown in the figure, as the orifice opening of multi-bypass 1 increases, the mass flow decreases obviously whether entering regenerator 2 or regenerator 3. And as the opening of multi-bypass 2 increases, the mass flow entering regenerator 3 decreases rapidly, but that entering regenerator 2 increases slightly. The reduction of the mass flow benefits the reduction of various internal loss in the regenerator, but adversely weakens the working ability of the gas in the regenerator and the cold head, as shown in Figs. 7 and 8.

4.2 Effect of two multi-bypass structures on characteristics along with the cold finger

The regenerator works as an efficient heat exchanger that is similar to a recuperative one, from the viewpoint of heat transfer. Smaller entropy generation is essential by reducing actual losses [38, 39], including pressure amplitude reduction loss, gas and matrix heat conduction losses, and irreversible heat exchange loss [2, 40]. Fig. 7 shows the changes of various internal losses in the regenerator with multi-bypass 1 or multi-bypass 2. As shown in the figure, pressure reduction loss and heat

exchange loss account for a large proportion, which will weaken the working ability of the gas and directly reduce the net cooling capacity of the cold head. The employment of multi-bypass 1 or multi-bypass 2 can effectively reduce these losses in the regenerator. Comparatively, multi-bypass 1 with a larger opening can more effectively reduce pressure reduction loss, heat exchange loss and gas conduction loss. This is because multi-bypass 1 operating in a higher temperature range,

can simultaneously reduce the mass flow entering regenerator 2 and regenerator 3, as shown in Fig. 6(a).

Under ideal operating conditions, the theoretical cooling capacity of SPTC is equal to the acoustic power or the average enthalpy in the pulse tube [40]. Actually, there is a deviation due to internal losses mentioned above in the regenerator and other losses in the pulse tube. Figs. 8 and 9 show the changes of acoustic power and enthalpy flow along with the cold finger with

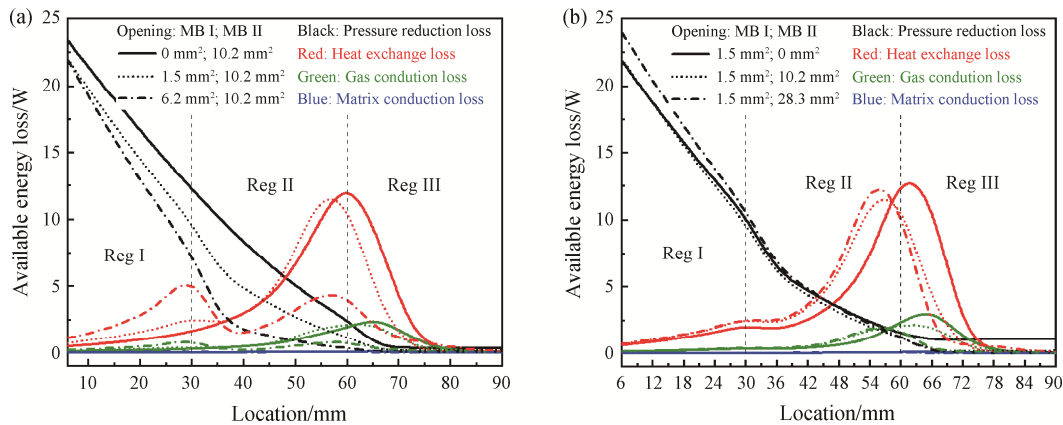


Fig. 7 Impact of two multi-bypass structures on exergy loss in the regenerator

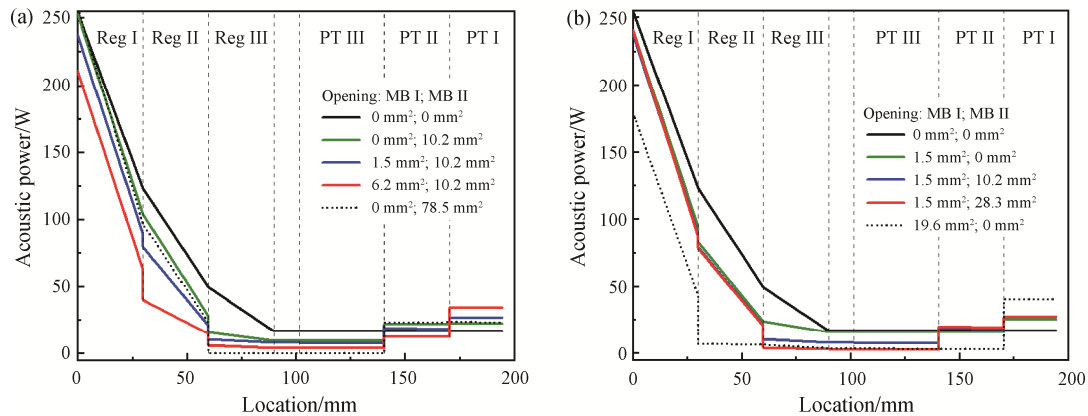


Fig. 8 Impact of two multi-bypass structures on acoustic power along with the cold finger

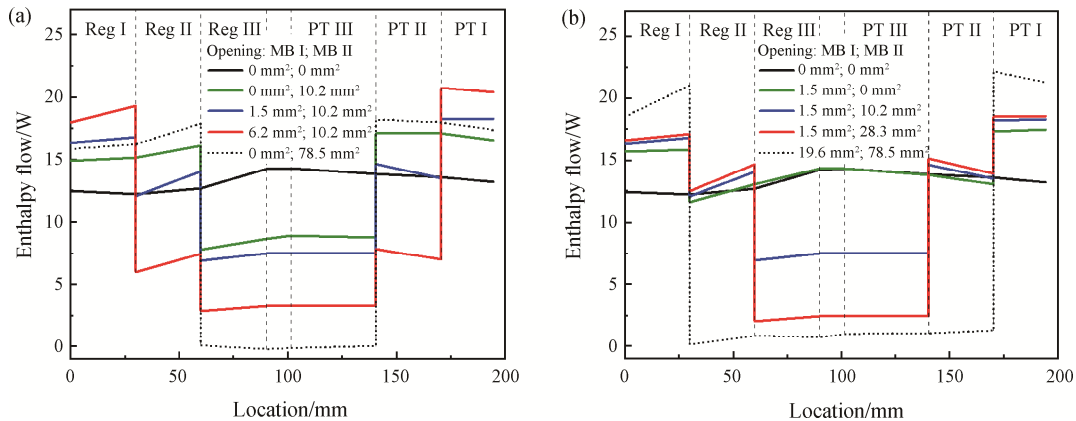


Fig. 9 Impact of two multi-bypass structures on enthalpy flow along with the cold finger

multi-bypass 1 and multi-bypass 2. As shown in the figures, the employment of multi-bypass 1 or multi-bypass 2 with a relatively smaller opening can increase the acoustic power and the enthalpy flow in pulse tube 1 or 2, which indicates that the working gas of the higher-temperature section can generate a pre-cooling effect on the lower-temperature section. Multi-bypass 1 or multi-bypass 2 with an excessive opening will reduce the acoustic power or the enthalpy value to near zero, which indicates that the working gas can no longer provide pre-cooling capacity. Moreover, with an abutting joint of regenerator 1 and pulse tube 1, or regenerator 2 and pulse tube 2, the acoustic power and the enthalpy flow become continuous and there is a slight deviation between them as that in regenerator 3 and pulse tube 3, which indicates regenerator 1, multi-bypass 1 and pulse tube 1 may constitute the first-stage structure, and regenerator 2, multi-bypass 2 and pulse tube 2 can also be regarded as the analogous second-stage structure.

Figs. 10 and 11 show the changes of the temperature and the phase angle along with the cold finger with multi-bypass 1 and multi-bypass 2. It can be seen that the appropriate employment of multi-bypass 1 or multi-bypass 2 can significantly reduce the intermediate

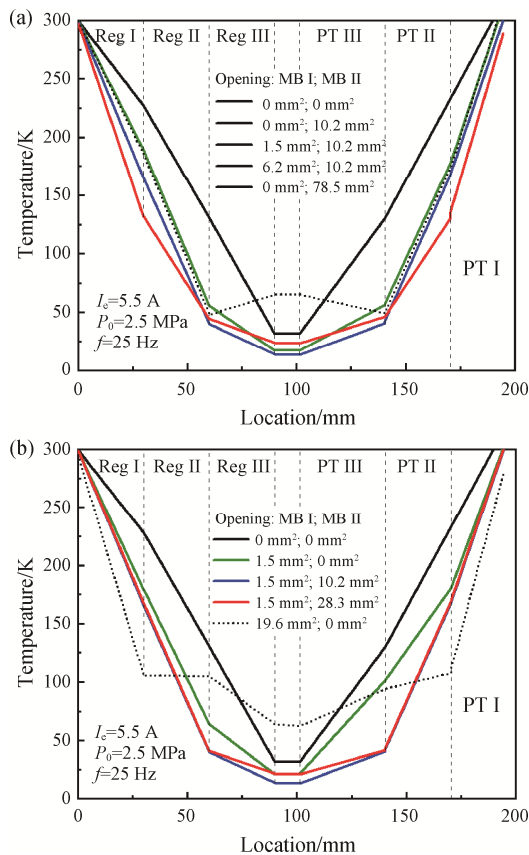


Fig. 10 Impact of two multi-bypass structures on temperature along the cold finger

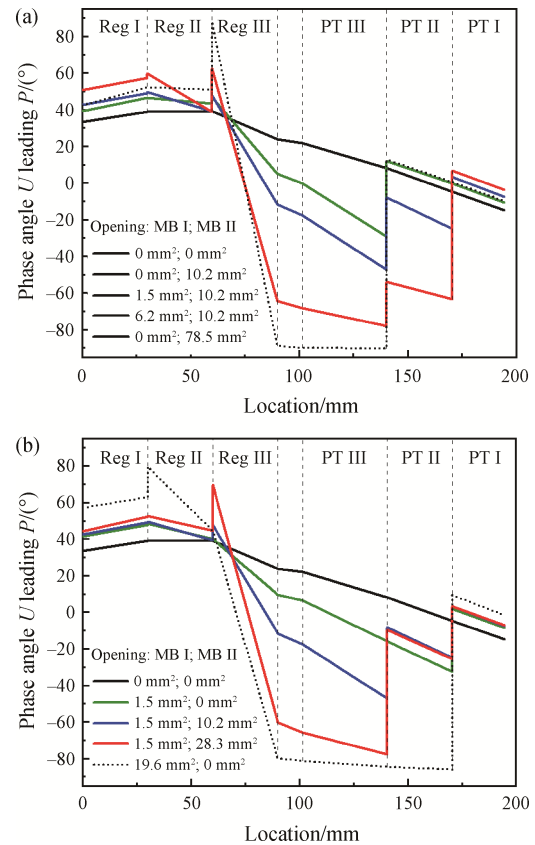


Fig. 11 Impact of two multi-bypass structures on phase angle along the cold finger

temperature of the regenerator, which also indicates multi-bypass can produce a pre-cooling effect at the employment position. Moreover, with an abutting joint of regenerator 1 and pulse tube 1 or regenerator 2 and pulse tube 2, the change of the phase distribution characteristics therein is consistent to that in regenerator 3 and pulse tube 3, which also indicates the segmental regenerator, multi-bypass and segmental pulse tube may constitute a similar single-stage structure. Additionally, the multi-bypass with a smaller opening can effectively improve the phase distribution characteristics along with the cold finger. But an excessive opening will dramatically deteriorate the phase angle of the partial position and the cold head, where the phase angle even approaches 90 degrees. In these situations, the lower-temperature section can almost be considered as a basic type SPTC, which loses the cooling function and completely becomes a thermal load, as shown in Figs. 10 and 11.

5. Development of the Two-Stage Gas-Coupled Multi-Bypass SPTC

As mentioned above, the multi-bypass with an excessive opening can produce a lower pre-cooling

temperature, but reduce the mass flow of the working gas entering the lower-temperature section due to excessively small flow resistance and deteriorate the phase angle of the employment position. In this section, inertance tube 2 and reservoir 2 are attached to multi-bypass 1 to enhance the flow resistance and the phase-shifting capability here, which also promotes the evolution of multi-bypass 1 into the cryogenic double-inlet. The schematic of the developed two-stage multi-bypass SPTC is shown in Fig. 12. After attaching the corresponding phase shifter, the impedance of the whole system might change, and structural parameters, matrix materials, and other operating conditions should be re-optimized. Table 2 gives some parameter details after optimization.

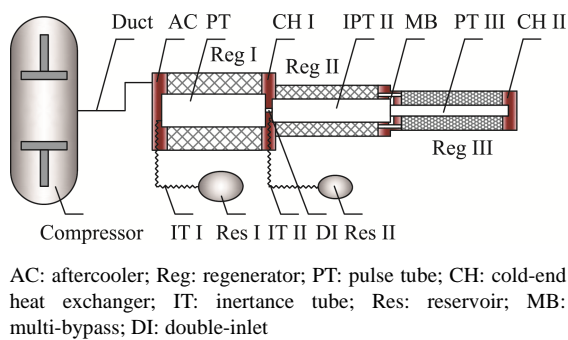


Fig. 12 Schematic of the completely two-stage gas-coupled multi-bypass SPTC

Table 2 Parameter details of the developed two-stage gas-coupled multi-bypass SPTC

Operating parameter	Value
Working gas	He-4
Input electric power	400 W
Input current amplitude	5.5 A
Charge pressure	2.25 MPa
Operating frequency	25 Hz
Structural parameter	Value
Reg I length/diameter	31 mm/26 mm
Reg II length/diameter	43 mm/18 mm
Reg III length/diameter	46 mm/12 mm
PT I length/diameter	47 mm/12 mm
PT II length/diameter	48 mm/9 mm
PT III length/diameter	51 mm/5 mm
IT I length/diameter	2 m/2 mm+2 m/3 mm+2 m/5 mm
IT II length/diameter	0.5 m/1 mm+1 m/2 mm
Res I volume	600 cm ³
Res II volume	80 cm ³
Regenerator matrix	Material
Reg I	304 stainless steel mesh (SS)
Reg II	304 stainless steel mesh (SS)
Reg III	Er ₃ Ni+HoCu ₂

5.1 Gas and phase distribution characteristics

Fig. 13 shows the variation of mass flow rate into regenerator 2 or regenerator 3 of the developed two-stage multi-bypass SPTC with multi-bypass or double-inlet opening. It can be seen that compared with the variations in Fig. 6, the mass flow of the working gas decreases obviously whether entering regenerator 2 or regenerator 3. The reasons are that after optimization, the charge pressure and the diameters of regenerators 2 and 3 are significantly reduced. Additionally, with the increase of the multi-bypass opening, the mass flow into regenerator 2 increases more evidently. And with the increase of the double-inlet opening, the mass flow into regenerator 2 or regenerator 3 decreases more slightly, which indicates that through the attachment of inertance tube 2 and reservoir 2, a relatively larger orifice will not excessively reduce the mass flow entering the lower-temperature section.

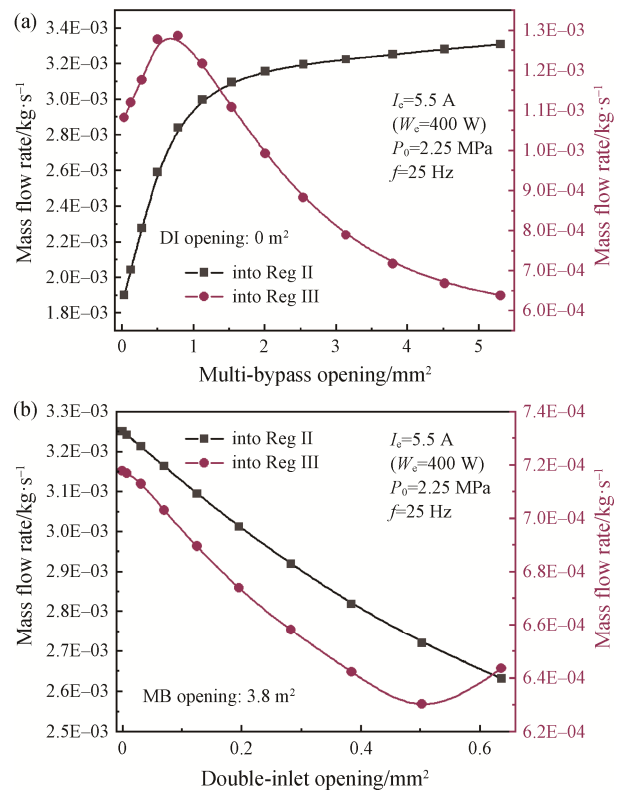


Fig. 13 Impact of multi-bypass and double-inlet on the mass flow of working gas

Figs. 14 and 15 show the variation of the phase angle with different multi-bypass or double-inlet openings along with the cold finger or at partial positions of developed two-stage multi-bypass SPTC. As shown in these figures, with an abutting joint of regenerator 2 and pulse tube 2, the change of phase distribution characteristics therein is consistent with that in the first-stage. Moreover, it can also be seen that due to the

attachment of inertance tube 2 and reservoir 2, a relatively smaller orifice can produce a powerful phase-shifting capability. Specifically, compared with the phenomena in Fig. 11, the double-inlet or the multi-bypass with a narrower adjustment range can more widely change the phase angle at the warm end of pulse tube 2 or at the cold end of pulse tube 3, and simultaneously can more effectively suppress the changes of the phase angles at the warm end of regenerators 2 and 3.

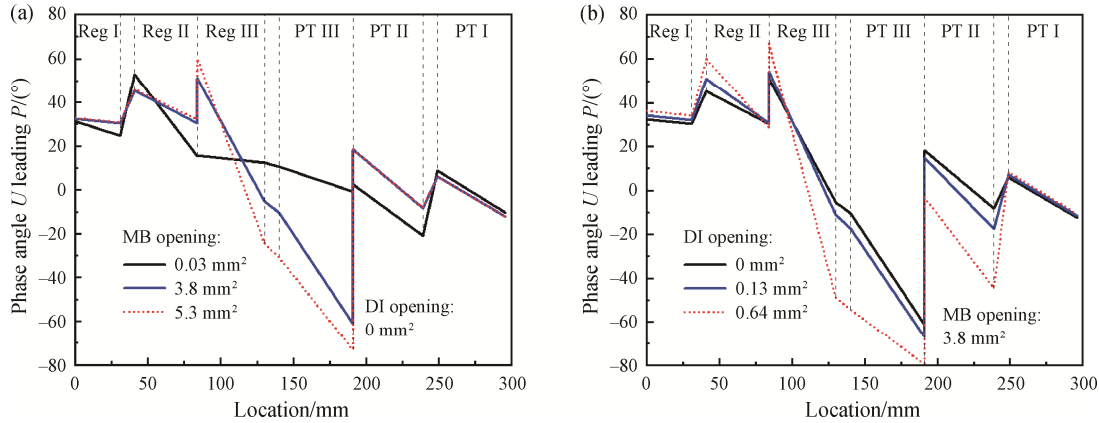


Fig. 14 Impact of multi-bypass and double-inlet on the phase angle along with the cold finger

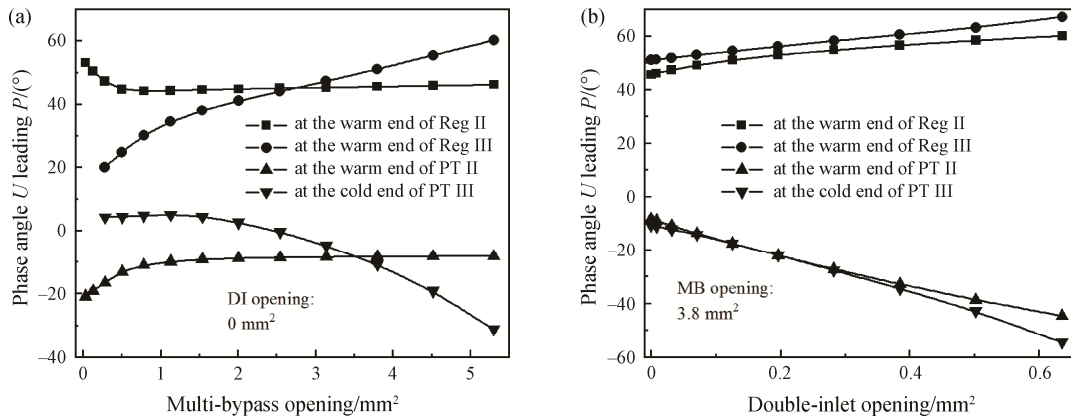


Fig. 15 Impact of multi-bypass and double-inlet on the phase angle at partial positions

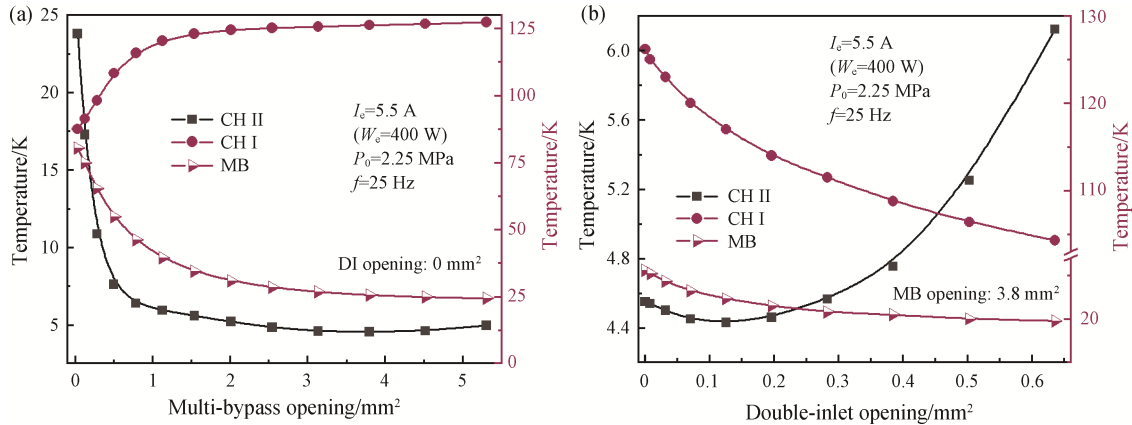


Fig. 16 Impact of multi-bypass and double-inlet on the cooling temperature

5.2 Cooling performance

Fig. 16 shows the variation of cooling temperature at the first-stage cold head, multi-bypass, or the second-stage cold head with different multi-bypass or double-inlet openings. It can be seen that compared with the lowest temperature in Fig. 5, after the attachment of inertance tube 2 and reservoir 2, the cooling performance can be greatly improved. Specifically, under the optimal operating conditions, without the multi-bypass and the double-inlet, the developed two-stage gas-coupled SPTC

can only obtain the lowest temperature of around 24 K. The multi-bypass with an optimal opening can more effectively reduce the lowest temperature to 4.6 K. The employment of the double-inlet can further reduce the no-load temperature of second-stage cold head to 4.4 K, where the corresponding temperatures of the first-stage cold head and multi-bypass are 117 K and 22 K, respectively.

6. Conclusions

This paper conducted systematic theoretical analyses of a gas-coupled multi-bypass SPTC and aimed at directly reaching a temperature of around 4 K. The whole design and optimization process of this cryocooler were presented. First, the working mechanism of the multi-bypass and the double-inlet employed in a single-stage SPTC was numerically studied and compared. Then, the coupling adjustment of two multi-bypass structures was also simulated and analyzed. Finally, a completely two-stage gas-coupled multi-bypass SPTC was developed by attaching an inertance tube and a reservoir to one of two multi-bypass structures. And this model obtained a temperature of around 4 K. Some conclusions are summarized as follows:

(1) Multi-bypass can be considered as the double-inlet working at a lower temperature range, and has all functions of the double-inlet, including increasing the acoustic power and the pressure ratio in the pulse tube, and adjusting the phase characteristics at the warm end of the pulse tube.

(2) Compared with the double-inlet, the multi-bypass operating at the middle or near the cold end of the regenerator can more effectively improve the cooling performance, which stems from the decrease of the acoustic power at the entrance of the regenerator and the weakening of working ability of gas in the regenerator and the cold head.

(3) Multi-bypass is similar to a multi-stage gas-coupled structure, and can produce a pre-cooling effect on the lower-temperature section by increasing the acoustic power and the enthalpy flow in the pulse tube of the higher-temperature section. The coupling of two multi-bypass structures can further improve the cooling performance, but it is difficult to achieve the same cooling performance of a completely multi-stage gas-coupled SPTC due to weak phase-shifting capability and excessive reduction of the mass flow.

(4) The attachment of the inertance tube and the reservoir can further promote a higher enhancement of the cooling performance. After the attachment of the corresponding phase shifter, the multi-bypass can more responsively improve the phase characteristics and more effectively stem the decrease of the mass flow, thus

ensuring the sufficient cooling function of the gas in the lower-temperature section.

Acknowledgments

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