Pulse tube refrigerator with shared inertance tube

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Background

Stirling pulse tube cryocoolers (SPTCs) have been widely used in the fields of superconductors, aerospace, industrial gas liquefaction etc. [1]. Efficient regenerative cryocoolers operate based on proper phase relations between pressure and mass flow. The progress of the pulse tube refrigerators is benefit from the inventions and discoveries of phase shifters. the inertance tube stands out for its simplicity and reliability, making it one of the most commonly used phase shifter for pulse tube cryocoolers in space applications[2]. For Small-scale SPTCs with limited cooling capacity, the small diameter of the inertance tube leads to a predominance of viscous resistance, which affects the phase-shifting capacity of the inertance tube[3]. For multistage SPTCs operating at temperatures below 20 K, relying solely on the inertance tube as a phase shifter in the low-temperature stage is insufficient[4].

The novel concept of the shared inertance tube SPTC has been developed[5]. In this structure, a multi-stage refrigeration system is driven by a step piston compressor, with the shared inertance tube connecting the hot ends of the pulse tubes. This structure enables the redistribution of the phase shifting ability at the hot end of the pulse tube, thereby enhancing the refrigeration capacity of the low-temperature stage and ultimately improving the overall efficiency of the multi-stage SPTC. The shared inertance tube diameter is also larger than ordinary inertance tube, which reduces frictional losses and heat transfer loss within the tube, thereby enabling the refrigeration system to achieve greater phase-shifting capacity.

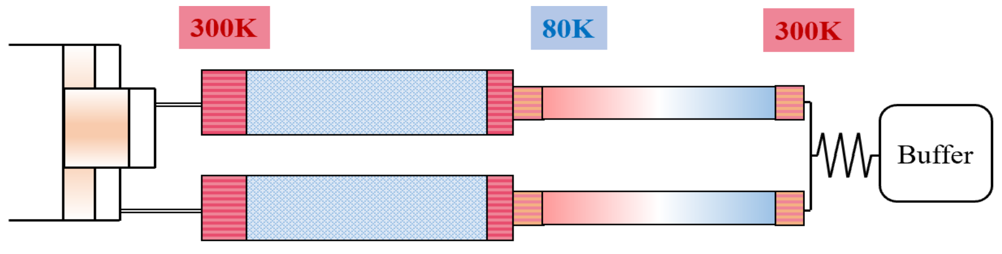


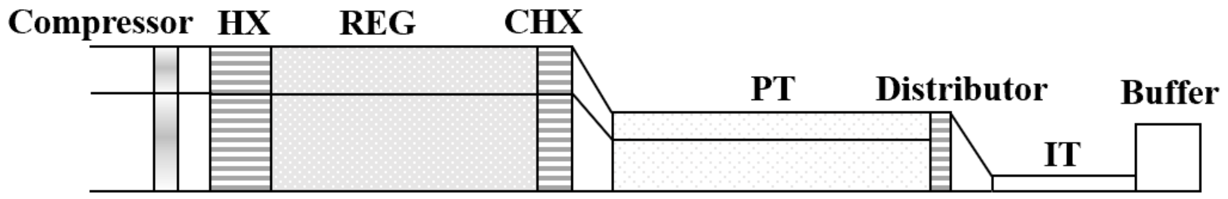
Figure 1. Schematic of the shared inertance tube SPTC

Before conducting research on the multi-stage shared inertance tube SPTC, numerical and experimental investigations will be carried out on a shared inertance tube SPTC with two same cold heads to validate the feasibility of this configuration. Additionally, a comparative evaluation of phase-shifting capacity and overall performance will be undertaken between the shared inertance tube SPTC and single-stage SPTC.

Reference:

[1] Radebaugh R. 2000, Proceedings of the Institute of Refrigeration, 96.
[2] Radebaugh R, Lewis M, Luo E, Pfotenhauer JM, Nellis GF, Schunk LA, 2006, Advances in Cryogenic Engineering, 823, 59-67.
[3] Luo E, Radebaugh R, Lewis M. 2004, AIP Conference Proceedings, 710(1), 1485-1492.
[4] Yin W, Liu SS, Song JT, Wu WT, Hui HJ, Jiang ZH, et al, 2023, Journal of Thermal Science, 32(6), 2155-2165.
[5] Zhu SW, 2009, Low temperature refrigerator. Japan: AISIN CORPORATION.

Numerical simulation model of the shared inertance tube SPTC



- The pressure inlet is set as $P=P_0+P_a \cdot \sin(2\pi ft)$.
- Standard k-omega model and Pressure-Based Segregated PISO algorithm.
- As a control group, a single-stage SPTC with a single cold head is also simulated. The geometric parameter of the cold head is the same as that of a shared inertance tube SPTC shown in Table 1.

Table 1. Geometric parameters of the cold head and phase shifter

Components	Geometric Parameters	Boundary conditions
HX	Φ24.8*65 mm	isothermal
REG	Φ24.8*65 mm	temperature gradient
PT	Φ14 mm*102 mm	adiabatic
Cold HX	Φ14 mm*8 mm	isothermal

Components	Shared inertance tube SPTC	Single-stage SPTC
IT length	1.8 m	1.8 m
IT diameter	6 mm	4.24 mm
Buffer volume	2 L	1 L

Numerical simulation results

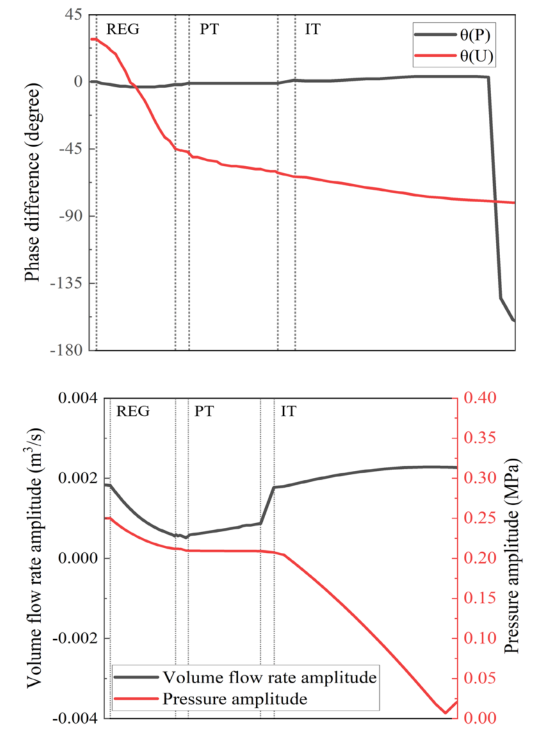


Figure 2. Axis distributions of the volume flow rate amplitude, pressure amplitude and phase difference. (L_{it}=1.8 m, D_{it}=6 mm, Freq=70 Hz)

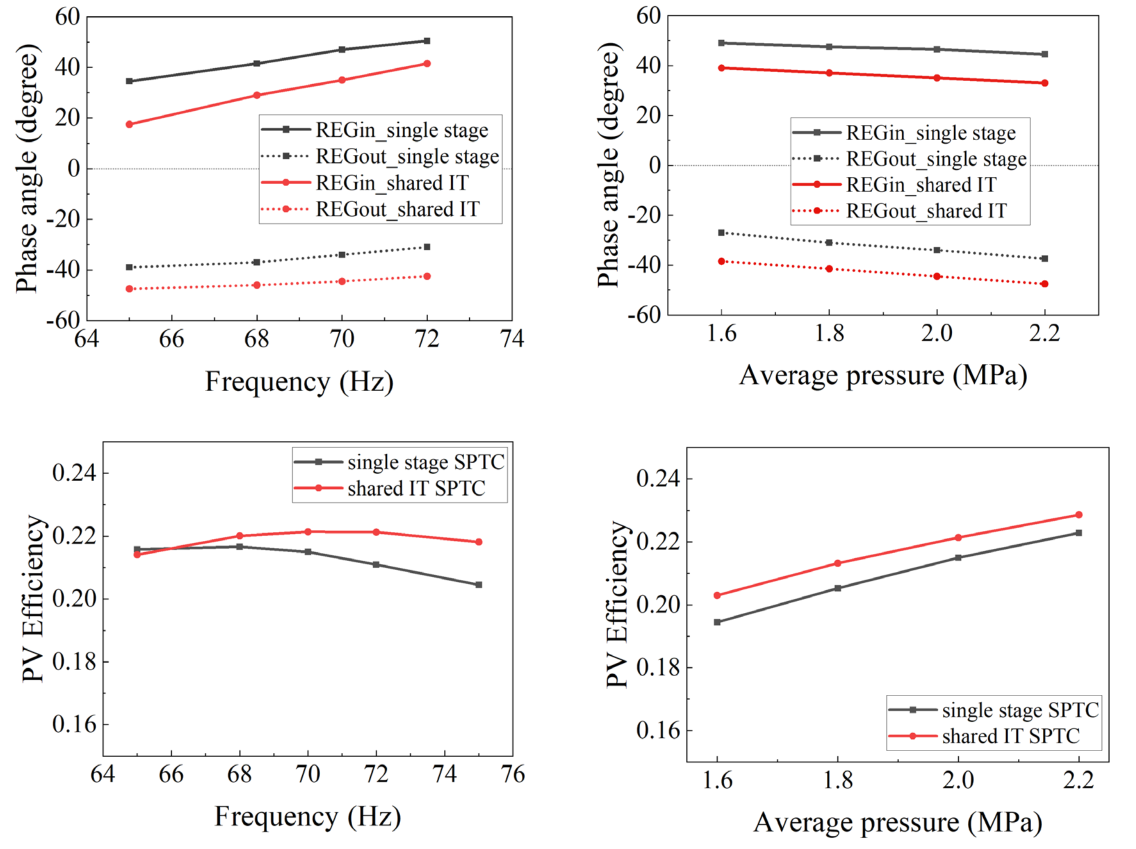


Figure 3. Phase angle (A positive phase angle indicates that the mass flow leads the pressure) and PV efficiency under different frequency and average pressure

- The mass flow and pressure amplitude of inertance tube inlet and pulse tube outlet has the relationship of: $\boldsymbol{m_{it} = m_{1,pt} + m_{2,pt} = 2m_{1,pt} = 2m_{2,pt}}$; $\boldsymbol{P_{it} = P_{1,pt} = P_{2,pt}}$.
- The necessary in-phase relationship is achieved at the centre of the regenerator, signifying the optimal acoustic fields.
- The shared inertance tube SPTC has superior phase-shifting capability.
- Both types of cryocoolers exhibit similar response trends to variations in frequency and pressure ratio. As the frequency increases, the phase shift ability of the cryocoolers diminishes.

Experiment

Figure 4. Experimental setup

- The stepped piston compressor is replaced by two identical compressors. The current passing through the compressors is the same and the two cold heads are also identical.
- It can be assumed that the phase and amplitude of the piston motion in both compressors are the same.

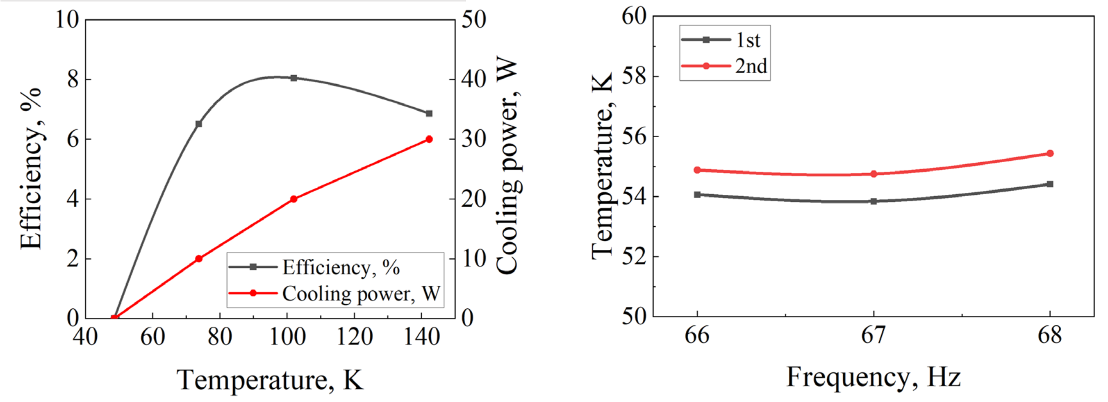


Figure 5. Efficiency and Temperature of the shared inertance tube SPTC

- The cold heads achieved the lowest temperatures of 53.8 K and 54.7 K at a total input power of 335 W, respectively, indicating good uniformity with a temperature difference within 1 K (L_{it}=1.75 m, D_{it}=6 mm).
- Upon increasing the power to 445 W, the two cold heads individually achieved a no-load cooling temperature of 48.5 K and 49.5 K, respectively. The overall cooling efficiency reached 8%@102 K.

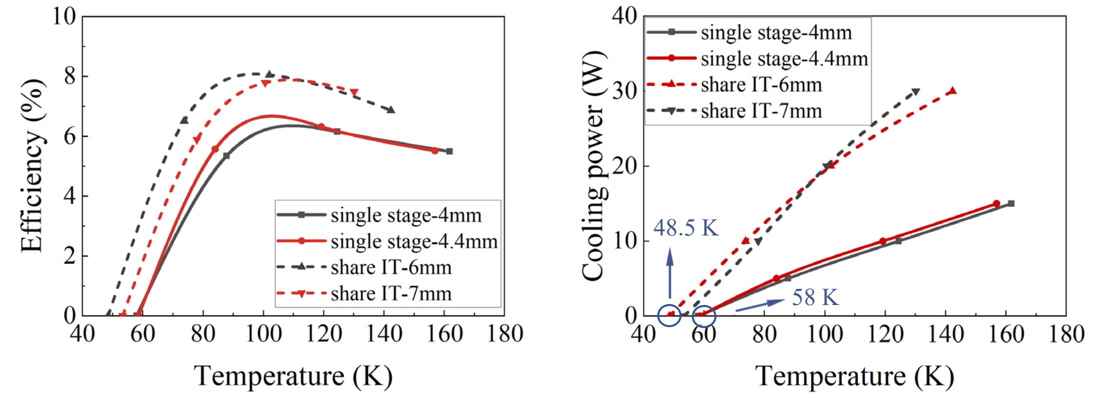


Figure 6. Efficiency and Cooling power of the two types of SPTC

- The experiments conducted on the single-stage SPTC (with an input power of half that of the shared inertance tube SPTC) were compared with those of the SPTC with a shared inertance tube, as depicted in Figure 6. Several sets of data were obtained with the inertance tube length being uniformly 1.75 meters.
- The SPTC with a shared inertance tube can achieve lower cooling temperatures and attain higher cooling efficiency in comparison to the single-stage SPTC.

Conclusion

Numerical simulations and experimental results demonstrate that the SPTC with a shared inertance tube possesses superior phase-shifting capacity compared to the single-stage SPTC. This configuration not only achieves lower cooling temperature but also exhibits higher efficiency. The two cold heads of the shared inertance tube SPTC achieved a no-load cooling temperature of 48.5 K and 49.5 K, respectively.

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