Experimental Research of 300 Hz Pulse Tube Cryocoolers

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ABSTRACT

This paper describes pulse tube cryocoolers (PTCs) that operate at 300 Hz and aim at reaching temperatures as low as 80 K. Two kinds of PTCs have been fabricated, tested and compared: in-line and coaxial. Different aspects of the performance of the PTCs have been investigated, especially the effect of the phase shifter. Unlike the conventional orifice valve, a fixed double-inlet nozzle has been used to shift the phase, as well as an inertance tube. A thermoacoustic driver was adopted as the pressure oscillator, supported by the thermoacoustic group of Dr. Luo of TIPC/CAS. After a series of optimization experiments, the in-line cooler reached 79.7 K and lifted about 1 W at 120 K with an inlet pressure wave amplitude of about 0.18 MPa at a filling pressure of 4.0 MPa.

INTRODUCTION

In the past twenty years, pulse tube cryocoolers have made great progress,[1,2] and the cooling performance of low-frequency G-M type and high-frequency Stirling type PTCs has approached the performance of conventional G-M and Stirling coolers. This indicates that wide use of PTCs is coming. The weight and dimensions of the Stirling-type PTC are about 10 times smaller than those of the G-M type. One approach to making the system compact is to use extra high frequency PTCs operating at above 100 Hz, and this needs a corresponding high-frequency linear-drive compressor—which is not easy work. Recently, the rapid development of 100-500 Hz thermoacoustic drivers provides a solution for testing high-frequency PTCs.[3-5] The work here utilizes such a pressure oscillator to drive the PTC.

For a PTC, there are some main features one needs to pay attention to: the diameter of pulse tube should be substantially larger than the thermal penetration depth of the working fluid, and the length of the pulse tube should be long enough to decrease the conduction loss and shuttle loss of the moving gas. Particularity, at our extra high frequency, the design of the regenerator is even more important, and needs more effort because of the poor heat transfer and large flow resistance.

DESCRIPTION OF EXPERIMENTAL SYSTEM

Our experimental system includes the pressure oscillator, regenerator, pulse tube, heat exchanger and the phase shifters. The pressure oscillator is a thermoacoustic driver provided by Dr. E.C. Luo

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Table 1. Dimensions of the two kinds of PTCs.

Type		Regenerator(mm)		Pulse Tube (mm)	
		Diameter	Length	Diameter	Length
In-line	PT1	10.5	35	5.5	40
	PT2	10.5	35	5.5	30
Coaxial	PT3	12.5	35	5.5	35

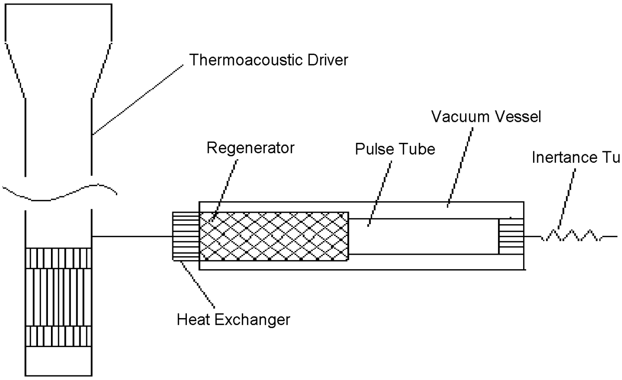

Figure 1. Schematic illustration of the experimental bench.

Figure 2. Photo of the experimental bench.

of our institute, and is cooled by circulating water. The pulse tube and regenerator are both composed of 0.2mm-wall-thickness stainless steel tubes, and are configured as both in-line and coaxial styles. Both of their hot ends are filled with copper mesh for distribution of flow and heat exchange. Detailed data are shown in Table 1. Temperature is measured using a standard PT100 platinum resistance thermometer, and its signal is sent to a computer via an IEEE488 interface, where it is recorded using a Labview program. The dynamic pressure is measured by a piezoelectric pressure sensor with sufficient responding speed. The pressure signal is amplified by a Type 5011 electronic amplifier and sent to an oscilloscope for real-time observation. A schematic illustration of the setup is shown in Fig. 1. Figure 2 is a photo of the experimental bench.

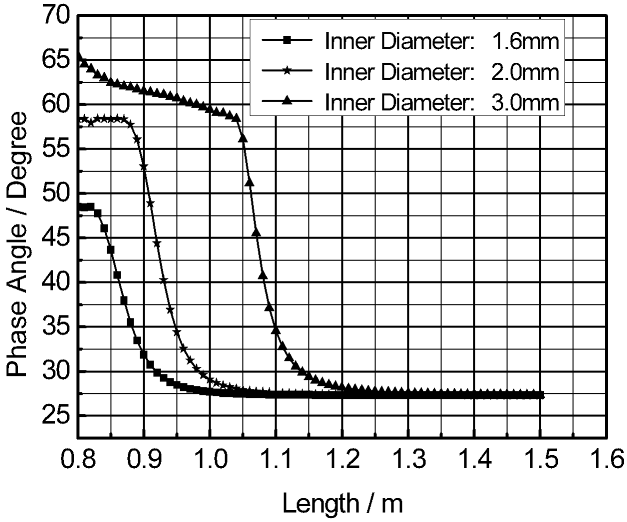

Figure 3. Change of PT1 coldtip phase.

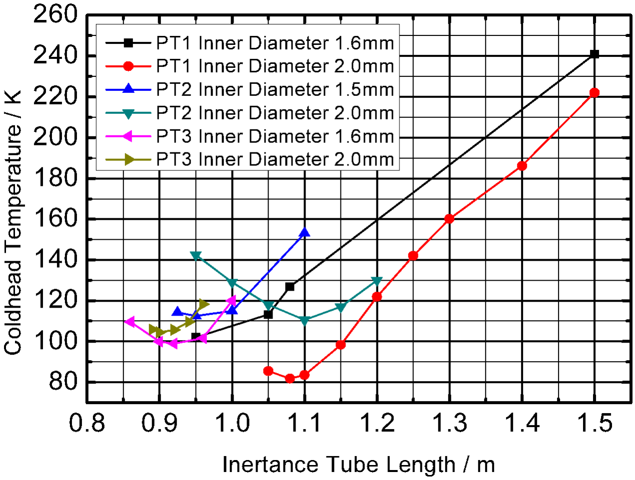

Figure 4. Performance of the three PTCs for different diameter inertance tubes.

EXPERIMENTAL RESULTS AND DISCUSSION

Many tests have been carried out on the experimental bench. The work has concentrated on the performance of the pulse tube cooler, with emphasis on adjusting the system phasing to optimize performance.

The inertance tube, key to adjusting the phasing, relies on its friction and inductance effect to improve the PTC performance. As the impedance of an inertance tube is proportional to the ratio of length-to-diameter, if one increases the diameter, the length must also be increased to get a similar impedance. Figure 3 is the simulated relation between the coldtip phase and the length of the inertance tube for different inertance-tube inner diameters on PT1.[6] According to the results displayed in Fig. 4, the minimum refrigeration temperature when using an inertance tube of 1.6 mm inner diameter is gained when the length is about 0.95 m; this corresponds to a phase difference between pressure and mass flow of about 30 degrees. Similarly, for the 2 and 3 mm inner diameter inertance tubes, the optimized lengths, respectively, are about 1.08 and 1.2 m; here the phase difference is also about 30 degrees. This could explain the phenomenon derived from the experiment that the optimized inertance tube length increases with the increase of inertance tube diameter.

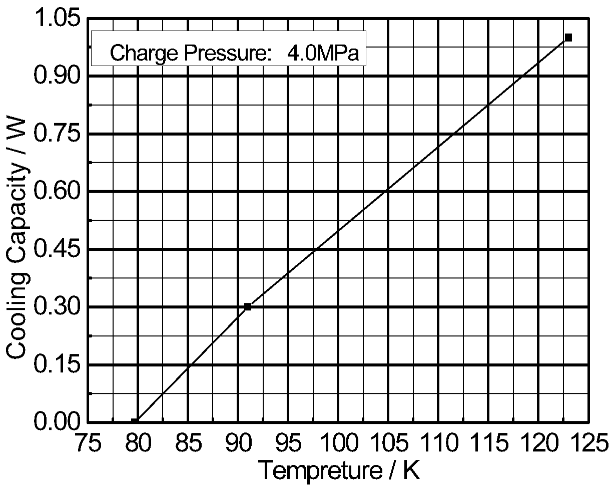

Figure 5. Cooling power of in-line PT1.

Figure 4 is the refrigeration temperature curve of the three PTCs vs. different inertance tube length. The results are without double-inlet nozzle. The effect of the ability of the inertance tube to shift the phase of the cold end is quite evident. Take the PT1 for instance, as the length changes from 1.5 m to 1.08 m, the temperature decreases from 221.94 K to 81.79 K. For all coolers, there is a minimum temperature point corresponding to the optimized inertance tube length. Also, we can see that for PT1 and PT2, the optimized inertance tube length increases with the increase of inertance tube diameter, which is in accord with the simulation; though PT3 is almost the same, it might be due to experimental error. In addition, by comparing the lowest cold head temperature of PT3 to that of the other two, our work suggests that the coaxial PTC needs a shorter length of inertance tube.

Shown in Figure 5 is the cooling power for in-line PT1. Though no-load temperature is one of the more important parameters for a pulse tube cooler, in practical use, attention is generally focused on the cooling power in some temperature zone. After a series of optimized experiments, the PT1 coldhead reached a no-load temperature of 79.7 K, and was able to lift about 0.3W at 90 K or 1 W at 120 K.

Shown in Figure 6 is the cold tip temperature vs. the diameter of the double-inlet nozzle. The experiment was carried out on the coaxial PTC with 4.0 MPa charge pressure and helium gas as the working fluid. The inertance tube length was kept unchanged at 0.92 m and 0.96 m, and the coldhead temperature increased about 2 K with a 0.2 mm nozzle, and then decreased with a nozzle diameter of 0.25 mm. With a 0.38 mm nozzle, the temperature rose. That might be because of DC flow.

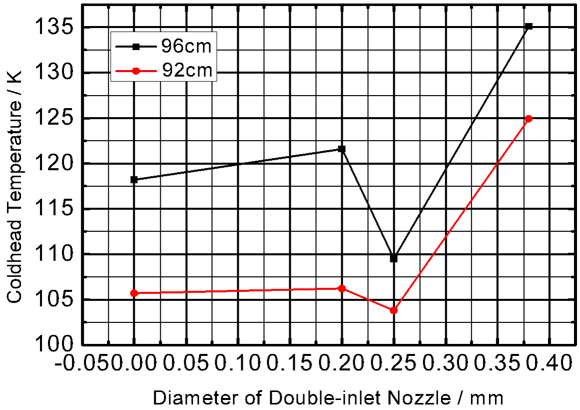

Figure 6. Relation of double-inlet nozzle and cold head temperature.

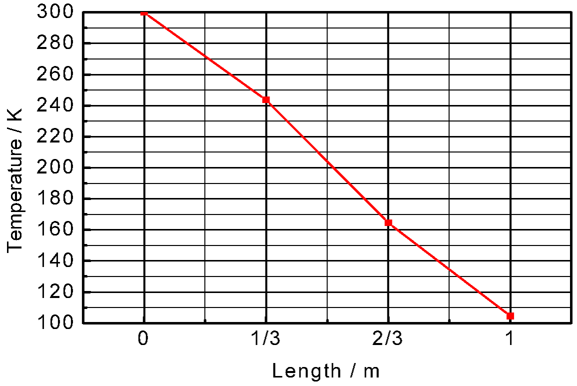

Figure 7. Temperature distribution of coaxial PT3.

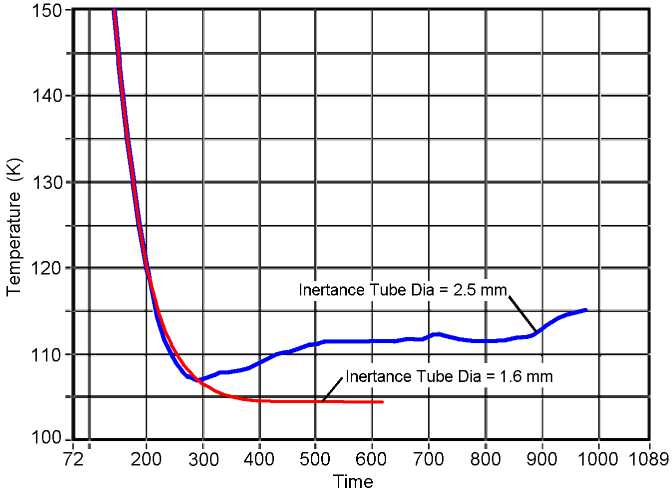

Figure 8. Cooling curve of coaxial PT3.

The temperature distribution along the regenerator tube is shown in Fig. 7. With a charge pressure of 4.0 MPa, the coldtip temperature finally dropped down to 104.25 K. The hot end is set to zero, and moving towards the cold end, at one and two thirds, two thermometers are employed to measure the temperature distribution along the regenerator temperature. Like in a conventional high frequency Stirling-type PTC, it is approximately a linear distribution.

Figure 8 shows cooldown curves of the coaxial PTC with two different inertance tube diameters. The special phenomenon is that the cold head temperature falls down to the lowest point and shifts upwards slowly when the inertance tube diameter is comparatively large, for instance, 2.5 mm. This unsteady phenomenon fades away with the decrease of the diameter, and comes to be completely steady when the diameter is 1.6 mm, whereas this phenomenon does not occur in the in-line pulse tube cryocooler. Further research needs to be done to understand this phenomenon.

CONCLUSIONS

This paper presents experimental results obtained on 300-Hz pulse tube cryocoolers. The performance of the pulse tube coolers is found to be greatly affected by the inertance tube. After a series of optimization experiments, one cooler reached a no-load temperature of 79.7 K and was able to lift about 1 W at 120 K. The experimental results show the complex influence of a double-inlet. An unsteady temperature phenomenon was found in the coaxial PTC, but was not seen in the in-line PTC.

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