A Thermoacoustically Driven Two-Stage Pulse Tube Cryocooler

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ABSTRACT

A thermoacoustically driven pulse tube cryocooler is a new type of cryocooler. Due to its heat-driven mechanism, no moving parts, and structural simplicity, this kind of system has become a focus of recent research in the field of cryocoolers. In this work, an efficient and low frequency coupling method was employed to couple a traveling-wave thermoacoustic engine and a two-stage pulse tube cryocooler (PTC). Due to this new coupling method, the pulse tube cryocooler can obtain a higher pressure ratio than that in the thermoacoustic engine, and the system can operate with a low frequency. During tests, the cooling temperature of this pulse tube cooler reached 32 K. Compared with some other pulse tube cryocoolers, the performance of this cryocooler is in fact not very good; some reasons for this are discussed.

INTRODUCTION

The thermoacoustic effect involves the thermodynamic interaction between an acoustic wave and contacted solid surfaces that poss a temperature gradient. Thermoacoustic engines and pulse tube cryocoolers are two important applications of the thermoacoustic phenomena [1]. In pulse tube cryocoolers, heat is pumped from a low temperature heat source to an ambient heat source by consuming mechanical work from an acoustic wave. In thermoacoustic heat engines, acoustic work is generated from a high temperature heat source. Thus, the combination of the two technologies gives birth to a new type of cryocooler with no moving components; this is commonly called a thermoacoustically driven pulse tube cryocooler [2].

In 1990, Swift and Radebaugh first succeeded in constructing such a heat-driven thermoacoustic cryocooler and obtained a no-load temperature around 90K [2]. Later on, they built a series of very large systems aimed at liquefying natural gas; these had kilowatts of cooling power at 120 K. In 2004, the no-load temperature of a heat-driven thermoacoustic cryocooler reached 80.9 K [3]. Recently, single-stage and two-stage pulse tube cryocoolers driven by an energy-focused thermoacoustic engine obtained lowest temperatures of 68.8 K and 41 K, respectively [4,5]. In fact, for Stirling-type pulse tube cryocoolers driven by a linear compressor, no-load temperatures below liquid hydrogen temperatures have been achieved [6, 7]. However, when driven by thermoacoustic engines, the achieved pressure ratio is much lower, and the operating frequency is higher; thus, they can not obtain the same low temperature.

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In the literature [8], we recently introduced a new efficient and low frequency coupling method for thermoacoustically driven pulse tube cryocoolers. In this method, the resonance phenomenon of a cavity is employed to improve utilization efficiency of acoustic power. By using an assembly of a long tube and a reservoir as an acoustic amplifier to couple the thermoacoustic heat engine with the pulse tube cryocooler, the cryocooler can obtain a higher oscillating pressure than that in the heat engine. Another characteristic of this coupling method is that an acoustically transparent, but gas blocking membrane, is installed between the engine and the cryocooler. Thus, the heat engine is allowed to use nitrogen as its working gas to operate at a lower resonant frequency; meanwhile, the cryocooler can still use helium as its working gas to achieve a lower temperature with high efficiency. Because of the increased oscillating pressure and the lowered operating frequency, a no-load temperature of 34.1 K was reached in our single-stage thermoacoustically driven pulse tube cryocooler [8].

Since the operating frequency is lowered for a single-stage pulse tube cryocooler, and the pressure ratio is also effectively improved, we have expected to obtain even lower temperatures with a thermoacoustically driven pulse tube cryocooler with more stages. Therefore, we want to develop a two-stage pulse tube cryocooler with the above-mentioned innovative thoughts. In this work, we present a detailed study of this new cryocooler.

EXPERIMENTAL SETUP

A schematic diagram of a Thermoacoustic Engine (TE) driven Pulse Tube Cryocooler (PTC) is shown in Fig. 1 and in Fig. 2(a). There are three principal subsystems: the traveling-wave TE, an acoustic amplifier, and the two-stage PTC. The long tube of the acoustic amplifier, shown in Fig. 2a, is connected to the engine near the water-cooled heat exchanger through a ball valve, and the reservoir of the amplifier is connected to the pulse tube cryocooler.

The Traveling-Wave Thermoacoustic Engine

The traveling wave thermoacoustic engine is composed of a loop and a tapered resonator. The loop is made of 80 mm inner diameter stainless steel tube with two water-cooled heat exchangers, a heater block, and a regenerator filled with 120 mesh stainless steel screens. The loop circumference is about 2 m. The resonator is composed of a 5 m long tapered tube changing from 80 mm to 300 mm in diameter, and a 1m long 300 mm diameter cylinder.

The Acoustic Amplifier

As we know, for many piping systems such as a tube with a reservoir shown in Fig. 2(a), when they are filled with a gas and the gas is vibrated by an oscillating pressure wave with some certain

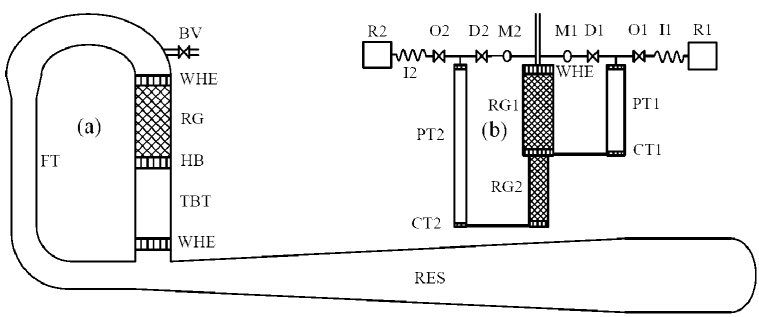

Figure 1. Schematic diagram of (a) a traveling-wave thermoacoustic heat engine and (b) a two-stage pulse tube cryocooler, with typical configurations used in our experimental setup. BV: ball valve; FT: feedback tube; WHE: water-cooled heat exchanger; REG, RG1, RG2: regenerators; HB: heater blocker; TBT: thermal buffer tube; RES: resonator; R1, R2: reservoirs; I1, I2: inertance tubes; O1, O2: orifices; D1, D2: double-inlet valves; M1, M2: DC flow suppresser; PT1, PT2: pulse tubes; CT1, CT2: cold tips.

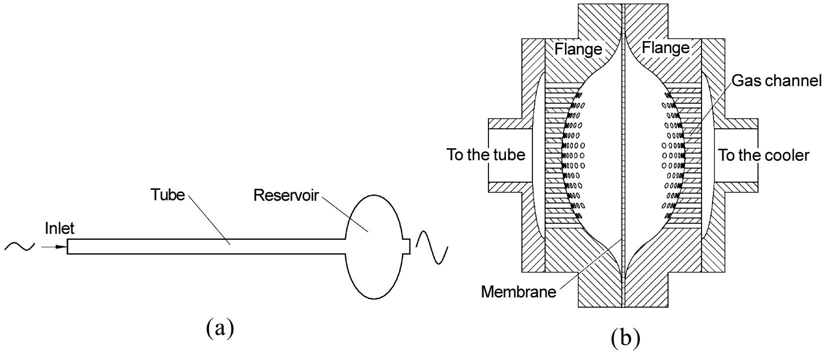

Figure 2. (a) A schematic diagram of an acoustic amplifier composed of a tube and a reservoir; (b) A cutaway view of the reservoir with a membrane.

frequencies at the inlet, the systems will resonate and the vibrations will be reinforced. At this time, the oscillating pressure and velocity at the inlet are in phase, which means the acoustic power flow is very large and the pressure amplitude is amplified at the closed end. So these systems can be employed to couple thermoacoustic heat engines with pulse tube cryocoolers to reach a driving pressure ratio for the PTCs.

In the thermoacoustically driven pulse tube cryocooler, the engine as a pressure wave source is connected with the inlet of the acoustic amplifier and the cryocooler is connected with the other end. Thus, the amplitude of the pressure in the cryocooler can be higher than that in the engine.

According to our calculations based on linear thermoacoustic theory, the bigger the tube diameter and the bigger the reservoir volume, the higher the amplification ratio will be (the pressure amplitude at the PTC inlet to that at the inlet of the acoustic amplifier) when the tube length is optimized. But, in practice, there is another factor limiting the diameter of the tube that can be used. As shown in Fig. 1, the acoustic amplifier is connected to the TE through a ball valve near the main water-cooled heat exchanger (the reason will be explained later). An additional volume flow from the acoustic amplifier will inevitably change the character of the loop when resonance occurs. This causes a decreased pressure ratio in the TE. In some worst cases, the valve can not be fully opened even when the temperature of the heater block is as high as 650°C. So a compromise between the amplification ratio and the performance of the TE must be made. After many experiments, an 8 mm diameter, 0.8 m long tube and a 64 cm^3 reservoir were chosen as the acoustic amplifier.

In order to separate the gas in the PTC from that in the TE, a membrane is installed at the middle section of the reservoir [8]. To protect the membrane from breaking, the reservoir is specially designed as shown in Fig. 2(b). Firstly, the cavity of the reservoir is cut into two half elliptical spheres and the membrane is held between the two half spheres. The cross-sectional area of the elliptical sphere is about 46 cm^2, which is much larger than that of the tube. Thus, the displacement of the membrane would be much smaller than that of the gas in the tube. Secondly, the cavity is connected to the tube and the PTC through many small gas tunnels. Their diameters are 1.5 mm. These gas channels promote propagation of the pressure wave from one side to the other side of the membrane; in addition, they prevent the membrane from departing too much from the middle point of the cavity. When the system begins to work, the mean pressure in the TE will increase because of heating and the mean pressure in the PTC will decrease because of cooling, the membrane will move toward the right. But the flange will stop its movement when the displacement is larger than the half height of the cavity. With the "help" of the flange, the membrane can tolerate a 3 MPa pressure difference between its two sides. By observing the pressure waveform at the inlet of the PTC through a pressure transducer, this configuration can also help us know whether the membrane touches the flange. If the waveform crest is distorted as shown in Fig. 3, it means that the membrane touches the right flange, and it is necessary to charge some helium into the PTC. Contrarily, if the wave trough is distorted, it means that the membrane touches the left flange, and it is necessary to vent some gas from the PTC.

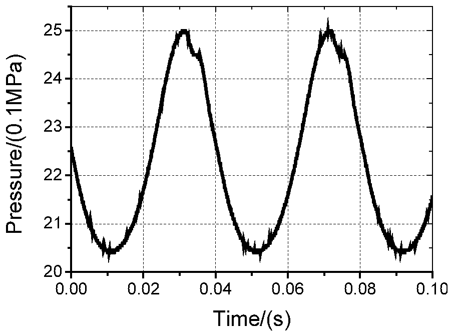

Figure 3. A typical pressure waveform with the crest distorted.

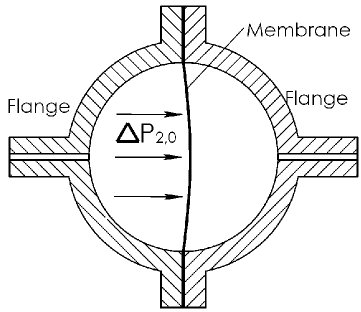

Figure 4. A cutaway view of the DC flow suppresser.

Table 1. Geometry parameters of the regenerator and pulse tubes of the two-stage PTC. The listed dimensions are: inner diameter×wall thickness×length (all in mm).

	Regenerator	Pulse tube
First stage	30× 0.2× 80 (400#)	15× 0.15× 70
Second stage	20× 0.15× 80 (500#)	10× 0.15× 160

The Pulse Tube Cryocooler

A ball valve is specially installed between the acoustic amplifier and the traveling-wave TE. If the valve is opened, the TE will not achieve startup even when the heating temperature is higher than 600ºC. So, in the experiment, the valve must be closed before the system starts oscillation, and then it is slowly opened with increase of the heating temperature.

The pulse tube cryocooler is a gas-coupled type as illustrated in Fig. 1(b). Both stages have a U-shaped configuration. The hot end of the first stage regenerator is pre-cooled by a water-cooled heat exchanger. The dimensions of the regenerators and the pulse tubes are listed in Table 1. Two double-inlet valves and inertance tubes with reservoirs are employed as the phase shifters. The first and second stage regenerators are filled with 400 and 500 mesh stainless steel screen, respectively.

As we know, the double-inlet mode often brings about a DC flow. If the DC gas flow is not well suppressed, the performance of the PTC will be greatly deteriorated. In this system, we have installed a DC flow suppresser between the PTC inlet and the double-inlet valve [7]. The suppresser mainly consists of two parts of half elliptical sphere-shaped cavity with a piece of elastic membrane held by the two flanges as shown in Fig. 4. The diameter of the elliptical sphere cavity is 30 mm (this dimension is determined according to the volume flow rate through the double-inlet valve); this is much larger than the connecting tube with a diameter of 3 mm.

EXPERIMENTAL RESULTS AND ANALYSIS

When 1650 W of heating power is input through the heater block, the heat engine filled with nitrogen begins to oscillate automatically at 23.5 Hz as soon as the gas temperature inside the heater block rises to above 90ºC. Then, the ball valve between the engine and the cavity can be slowly opened. When the gas temperature is higher than 300ºC, the valve can be fully opened. The pressure wave generated in the thermoacoustic heat engine is first amplified in the coupling amplifier, and then propagates into the pulse tube cryocooler filled with helium through the elastic membrane. After three hours, the gas temperature in the heater block is stabilized at about 580ºC, and the whole system reaches an energy balance. The pressure amplitude at the pulse tube cryocooler inlet is 0.203 MPa (pressure ratio 1.21), which is higher than that (0.163 MPa, pressure ratio 1.16) in the engine. Figure 5 presents the pressure waves at the two locations.

Although the operating frequency is very low, the cooling temperature only reaches 32 K, which is much higher than we expected. And the temperature of the first stage cold tip is also as high as

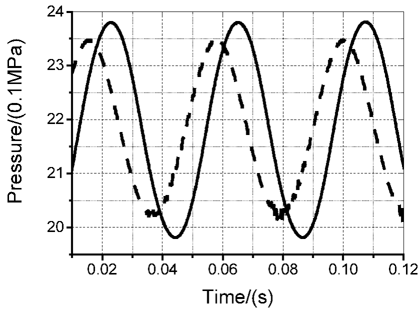

Figure 5. Two typical pressure waves when the system reached the energy balance. The solid line and dashed line present the pressure wave at the inlet of the PTC and in the TE near the main water-cooled heat exchanger, respectively.

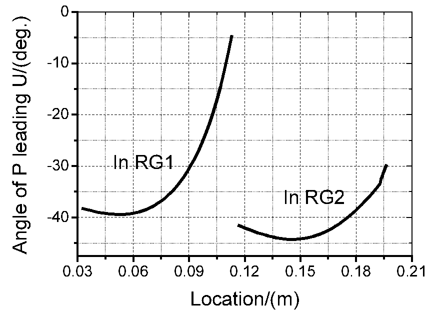

Figure 6. The distribution of angle pressure leading volume flow in the regenerators.

Table 2. Operating features of the two-stage pulse tube cryocooler.

	Driven by the TE		Driven by a compressor	
parameter	First stage	Second stage	First stage	Second stage
Temperature of the cold tips	102K	32K	98K	36K
Pressure amplitude in pulse tubes	0.17MPa	0.148MPa	0.287	0.21MPa
Pressure amplitude at the inlet	0.203M		0.35MPa	

102 K. Compared with some other two-stage PTCs [6, 7], the driven pressure ratio is relatively low. In order to find out the influence of the pressure ratio on the no-load temperature, a mechanical compressor was used to drive this PTC. With this compressor, the PTC could obtain a driving pressure ratio of 1.38 (pressure amplitude 0.35MPa). However, we found the performance of the PTC even further deteriorated. Table 2 presents the operating features of the two-stage pulse tube cryocooler. Thus, the problem seems not to come from the low pressure ratio.

Based on linear thermoacoustic theory, a numerical procedure was employed to analyze the cryocooler [9]. Figure 6 presents the distribution of phase angle of pressure leading velocity in the regenerators. We can see that this distribution is not reasonable. At the warm end of the regenerator, the volume flow rate leads the pressure too much, while at the cold end of the regenerators, the pressure does not lead the volume flow rate at all. This is not in accord with the common design principle that the pressure should lag the flow by about 30 degrees at the warm end the regenerator, and at the cold end, the pressure should lead the flow by about 30 degrees. So the dimension the PTC needs to be further optimized.

SUMMARY

A thermoacoustically driven two-stage pulse tube cryocooler was built and tested. In the system, an efficient and low-frequency operation coupling method was employed. With this new method, the pulse tube cryocooler obtained a pressure ratio of 1.21 and the system worked at about 23.5 Hz. Although the cooling temperature of this pulse tube cryocooler did not achieve the temperature of liquid hydrogen, a no-load temperature of 32 K was achieved.

Some reasons for the unsatisfactory performance of the cryocooler have been presented, and we are now optimizing the dimensions of this pulse tube cryocooler. We hope that this thermoacoustically driven two-stage pulse tube cryocooler will soon reach about 20 K.

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REFERENCES

1. Swift G.W., *Thermoacoustics: A unifying perspective for some engines and refrigerators*, Acoustical Society of America Publications, Sewickley, PA (2002), pp. 1-300.

2. Radebaugh, R., McDermott, K.M., Swift, G.W., et al., "Development of a thermoacoustically driven orifice pulse tube refrigerator," *Proceedings of the 4th Interagency Meeting on Cryocoolers*, *Plymouth MA, October 24, 1990*, David Taylor Research Center Document DTRC-91/003, January 1991, p. 205.

3. Qiu, L. M., Sun, D.M., Yan, W.L., et al., "Investigation on a thermoacoustically driven pulse tube working at 80 K," *Cryogenics,* vol. 45 (2005), pp. 380-385.

4. Dai, W., Luo, E., Hu, J., and Ling, H., "A heat-driven thermoacoustic cryocooler capable of reaching liquid nitrogen temperature," *Appl. Phys. Lett.*, vol. 86 (2005), pp. 224103.

5. Hu, J.Y., Dai, W., Luo, E.C., "Thermoacoustically driven pulse tube cryocoolers with acoustic amplifiers," *Adv. Cryo. Eng.*, vol.51 (2006), pp. 1564-1571.

6. Yang, L.W. and Thummes, G., "High frequency two-stage pulse tube cryocooler with base temperature below 20K," *Cryogenics*, vol.45 (2005), pp. 155-159.

7. Nguyen, C., Yeckley, A., Culler, A., et al., "Hydrogen/oxygen propellant densifier using a two-stage pulse tube cryocooler," *Adv. Cryo. Eng*., vol. 49 (2006), pp. 1703-1709.

8. Hu J.Y., Luo E.C., Dai W., "An efficient and low coupling method for heat driven thermoacoustic cryocooler," *Journal of Applied Physics* (2006), Submitted.

9. Hu, J.Y., Luo, E.C. and Dai, W., "An innovative configuration for thermoacoustically-driven pulse tube cryocoolers," *Cryogenics*, vol. 42 (2005), pp. 523-527.

10. Hu, J.Y, Daiv W. and Luov E.C. "A 41K heat-driven thermoacoustic cryocooler," *Chinese Journal of Engineering Thermophysics*, vol.27 (2006), pp. 189-192.