EXPERIMENTAL STUDY ON A HIGH FREQUENCY MINIATURE PULSE TUBE REFRIGERATOR WITH INERTANCE TUBE

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ABSTRACT

It is generally considered that the use of an inertance tube in a high frequency pulse tube refrigerator (PTR) improves the phase shift between the pressure and the mass flow rate. In order to investigate the effects of inertance tubes on the performance of a miniature PTR, experiments on the high frequency miniature PTR with inertance tube, orifice and bypass have been carried out. Inertance tubes with various inner diameters of 0.5mm, 1mm, 1.5mm, 2mm and different lengths from 1m to 7m were tested. Two fine needle valves were adapted as the orifice and the bypass. The experiments were performed under a charge pressure of 2.5MPa. The operating frequency is varied from 20Hz to 50Hz. Experimental results show that the inertance tube with inner diameter of 1.5mm and length of 2m is proper for the miniature PTR at high frequency. The benefit of using only an inertance tube is not apparent in miniature PTR. The lowest temperature achieved by the PTR with inertance tube is only 107.3K, which is higher than the lowest temperature of 101.6K achieved by the bypass PTR. The miniature PTR with both inertance tube and double inlet configuration has the lowest temperature of 89K. It is also found that the bypass configuration has the function of power recovery.

INTRODUCTION

Simplicity is one of the most outstanding features of pulse tube refrigerators (PTR) due to no moving parts in the cold end of regenerator and pulse tube. It brings advantages in longer lifetime and lower vibration. But the simplification in hardware produces difficulty in controlling phase angle between pressure and mass flow rate at the cold end of the PTR, which is the key parameter for the performance of PTR [1]. The first approach to achieve the proper phase angle is to place an orifice between the warm end of the pulse tube and the reservoir. The minimum phase angle of zero degree at the warm end of the pulse tube can be obtained through adjusting the orifice setting. However, the mass flow

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rate at the cold end of the pulse tube leads the pressure because of the pulse tube volume. Thus the amplitude of mass flow rate in the regenerator is large to transmit a given compressor work. It is generally believed that the larger amplitude of mass flow rate causes larger pressure drops as well as poorer heat exchange between the gas and the matrix in the regenerator [2]. Based on the orifice configuration, the bypass concept was introduced by connecting the compressor and the warm end of the pulse tube directly through a bypass. This configuration can efficiently regulate the phase relationship between the mass flow rate and the pressure at the cold end of the pulse tube. The bypass leads to increased efficiency of the PTR, but it also causes work losses in the second orifice and a DC flow [2]. Fortunately, there is another mechanism possible due to fluid inertia that could be used to give favorable phase shift.

Kanao et al. [3] reported a high frequency pulse tube refrigerator with capillary tube as phase shifter early in 1994. Their PTR was driven by a linear compressor with swept volume of 3cm^3. The experimental results showed an improvement of the PTR performance with the orifice and bypass configuration replaced by the capillary tube. Harayam et al. [4] reported the dependence of the lowest temperature on frequency and on the length of the capillary phase shifter for a miniature PTR. Zhu et al. [5] studied the effects of fluid inertia on PTR performance by using numerical simulations and simplified experiments. The compressor used in their experiments and simulations had a swept volume of 60cm^3. They considered it possible to achieve equivalent PV diagrams, similar to that of Stirling cooler, at the cold end of the pulse tube by using fluid inertia effects to control the phase angle. Gardner and Swift [6] investigated the fluid inertia effects on improving the phase angle between the pressure and the mass flow rate using an electrical analogy. They showed that the use of inertance might provide higher efficiency for larger PTRs, and that fluid inertia effects were also available for smaller PTRs. The works of Ravikumar et al. [7, 8] showed that fluid inertia effects had significant influence on the performance of PTRs at higher frequency. The inertance tube can not only provide a good phase shift at higher frequency, but can also amplify the pressure ratio in the pulse tube. Duband et al. [9] and Marquardt et al. [10] had successfully adapted inertance tubes in their practical PTRs.

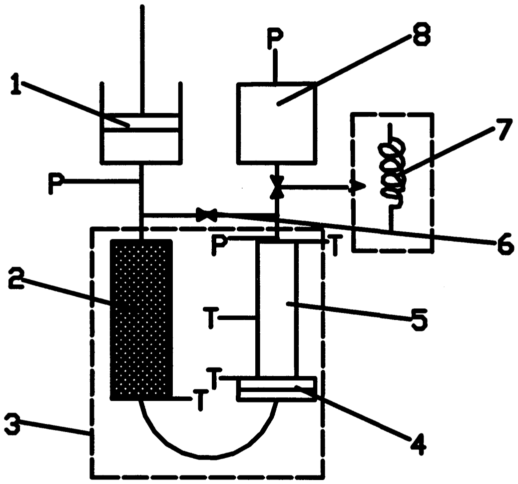

FIGURE 1. Schematic diagram of experimental set up. 1. Compressor, 2. Regenerator, 3. Vacuum chamber, 4. Cold head of pulse tube, 5. Pulse tube, 6. Bypass, 7. Orifice (can be replaced by inertance tube), 8. Reservoir, T. Type-T thermocouples, P. Pressure transducers.

Most of the works about the fluid inertia effects on the performance of PTR were carried out for relatively large PTR systems. This paper focuses on the effects of the inertance tube for a miniature PTR system.

EXPERIMENTAL SETUP

Figure 1 is a schematic of the experimental setup. The PTR is arranged in the "U" shape. The cold end of the regenerator is connected to the cold end of the pulse tube by a narrow copper tube. Two identical fine needle valves are used as the orifice and the bypass. They are placed outside of the vacuum chamber and are convenient to be adjusted. The orifice can be replaced by the inertance tube. With the orifice opened and the bypass closed, it is an orifice PTR. With both the orifice and bypass opened, it becomes a bypass PTR. If the orifice is substituted by the inertance tube, the PTR is called the inertance PTR. In the inertance PTR, the bypass valve can be closed or opened. The vacuum environment is maintained by a vacuum pump. A vacuum of 1.0Pa can be reached. The temperature is measured at the cold end of the pulse tube by using a copper-constantan thermocouple. Dynamic pressures are measured by the quartz pressure transducers in the hot end of the regenerator, in the hot end of the pulse tube and in the reservoir. The compressor is of rotary type and is estimated to be only about 50% efficient. It has a constant swept volume of 1.66cm^3. The compressor has been used for more than 10 years and has been severely worn out. After the compressor has been running for a short time, the layers of screen in the regenerator at the hot end are covered by some tiny brown powder. Thus the performances of the PTR was not impressive. The main construction parameters of the cold finger are listed as follows:

Pulse tube:	stainless steel tube	
	inner/outer diameter	5/5.2mm
	length:	75mm
Regenerator:	stainless steel tube	
	inner/outer diameter	7.8/8.2mm
	length:	60mm
Regenerator materials:	stainless steel screen	
	400-mesh	
Reservoir:	volume	59cm^3

MINIATURE PTR WITH INERTANCE TUBE

In the harmonic approximation, a simple electrical analogy of the PTR can provide a straightforward demonstration of the phase relation between the velocity and the pressure at the warm end of the inertance PTR [6, 9, 11]. Figure 2 is the electrical analogy of the phase shifting network at the warm end of the PTR. In this analogy the pressure and the volume velocity correspond to the voltage and current, respectively. The impedance Z is defined as

$$Z = \frac{\Delta p}{U_{hot}} = R + j\omega L + \frac{1}{j\omega C_r}, \tag{1}$$

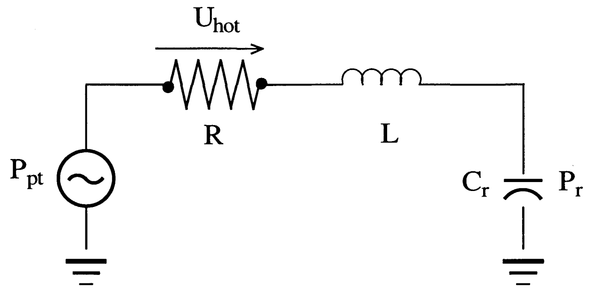

FIGURE 2. The electrical analogy using lumped circuit elements for the phase shifting net work at the warm end of the PTR.

Here Δp is the pressure difference between the pulse tube and the reservoir; U_{hot} is the volume velocity at the warm end; R, L are the resistance and the self inductance of the inertance tube, respectively; C_r is the capacitance of the reservoir, the capacitance of the inertance tube is neglected; ω is the angular frequency, $\omega = 2\pi f$, f is the operating frequency.

Generally, the reservoir is large enough to neglect the term $\frac{1}{\omega C_r}$. We assume that the pressure in the reservoir is constant, and the pressure in the pulse tube is uniform. Equation (1) can be simplified as:

$$Z = \frac{p_{pt}}{U_{hot}} = R + j\omega L, \tag{2}$$

where p_{pt} is the pressure in the pulse tube.

For a tube with an inner diameter d and a length l, the equivalent self inductance L and associated resistance R can be expressed for a laminar flow as [11]:

$$L = \frac{4\rho l}{\pi d^2}, \tag{3}$$

$$R = \frac{128\mu l}{\pi d^4}, \tag{4}$$

where ρ is the gas density; μ is the gas viscosity.

An efficient PTR requires that the oscillating velocity leads the oscillating pressure at the hot end of the regenerator and lags it at the cold end. A 30 degree lag at the cold end is the approximate optimum [2]. Since gas oscillating in a pulse tube of finite volume cause the velocity at cold end to lead the velocity at the warm end of the pulse tube, the velocity at the warm end must lag behind the pressure even further to 50-60 degree [2]. From equations (2), (3) and (4), the phase angle between the pressure and the volume velocity at the warm end of the pulse tube can be expressed approximately as:

$$\varphi = \tan^{-1}\frac{\omega L}{R} = \tan^{-1}\frac{\rho\omega d^2}{32\mu}. \tag{5}$$

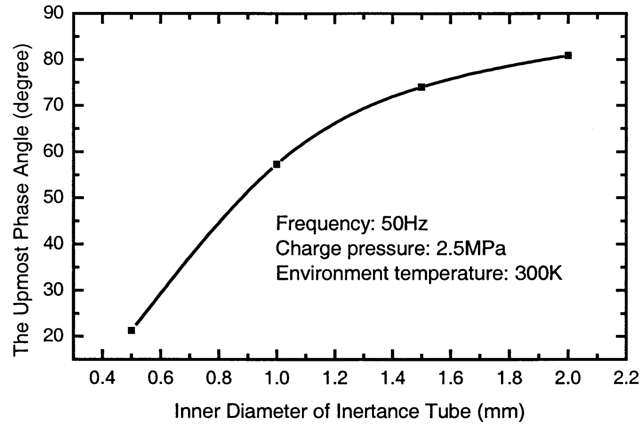

FIGURE 3. The upmost phase angle achieved by inertance tubes with different inner diameter.

Equation (5) is schematically showed in Figure 3. It seems that any phase angle between 0 to 90 degree can be obtained by selecting a suitable inner diameter of the tube. The larger the diameter is, the bigger the phase angle is. Unfortunately, the practical phase angle is less than the theoretical one because turbulence may occur in the inertance tube.

In order to investigate the effects of inertia on the performance of the miniature PTR, various copper inertance tubes with different inner diameter and length have been used as the phase shifters. Figure 4 represents the experimental results of capillaries with different length at inner diameter of 0.5mm. Since the radius is less than the viscous penetration depth of helium gas (which is about 0.3mm at 50Hz and 300K), these capillaries show almost no inertia effects and are really orifices. The lowest temperature of 114.3K is obtained by the capillary with length of 0.5m at 40Hz.

With the increasing of the tube diameter, the influence of inertia increases. Figures 5, 6 and 7 show that inertance tubes with inner diameters of 1mm, 1.5mm and 2mm have strong effects on the performance of PTR at higher frequency. There exists an optimum diameter and length of the inertance tube for a given PTR. It is found that the inertance tube with a diameter of 1.5mm and a length of 2m has the best effect, with which the lowest temperature of 107.3K is obtained.

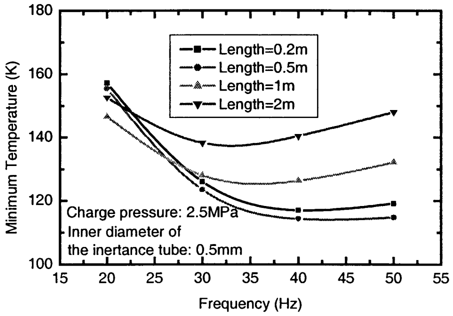

FIGURE 4. The lowest temperature as function of the length and operating frequency for the inertance tube with inner diameter of 0.5mm.

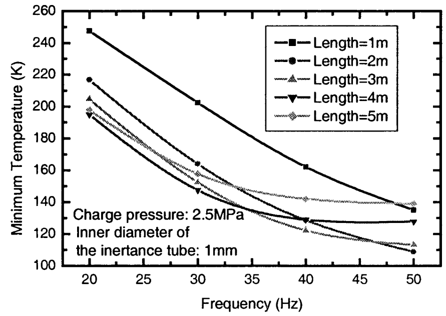

FIGURE 5. The lowest temperature as function of the length and operating frequency for the inertance tube with inner diameter of 1.0mm.

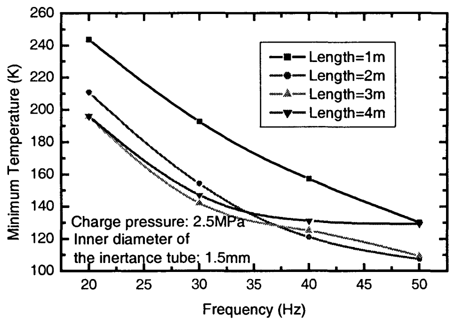

FIGURE 6. The lowest temperature as function of the length and operating frequency for the inertance tube with inner diameter of 1.5mm.

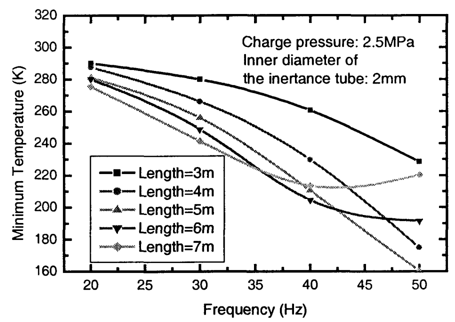

FIGURE 7. The lowest temperature as function of the length and operating frequency for the inertance tube with inner diameter of 2.0mm.

Theoretically, the inertance tube with inner diameter of 2mm has better phase shifting capacity, however, with which the PTR has a disappointing performance. Figure 8 shows that the pressure ratio in the pulse tube decreases with increasing inertance tube diameter. This means the theoretical refrigeration decreases. Thus inertance tubes with large inner diameter are improper for miniature refrigerator systems.

Table 1 is the comparison of the effects of different phase shifters. The lowest temperature achieved by the PTR using only an inertance tube as the phase shifter is only 107.3K, which is higher than the lowest temperature of 101.6K achieved by the PTR with the bypass configuration. From the previous discussion, the inertance tube suitable for the miniature PTR has an inner diameter of about 1.5mm. The flow inside such a small tube may be turbulent, this will cause a smaller phase shift, and will lead poor PTR performance.

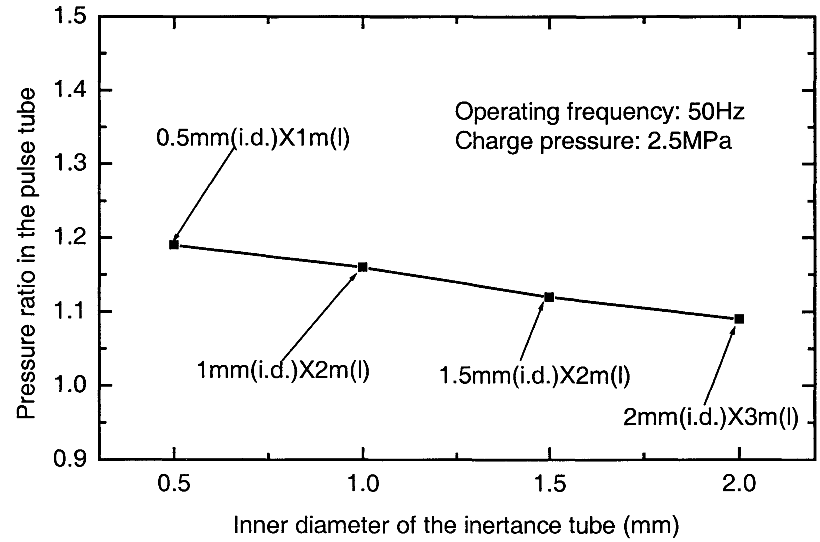

FIGURE 8. Variations of pressure ratio in the pulse tube as function of the inner diameter of inertance tube.

TABLE 1. Comparison of the lowest temperature achieved by various phase shifters.

Phase shifter	Orifice	Orifice+ bypass	Inertance tube
Minimum temperature	116.3K	101.6K	107.3K

Here the inertance tube is 2m long with 1.5mm inner diameter.

MINIATURE PTR WITH INERTANCE TUBE PLUS BYPASS

In order to achieve a desirable phase shift, the bypass has been implemented. Figure 9 shows the lowest temperature and power consumption versus the opening setting of the bypass valve. The lowest temperature achieved is 89K. Opening the bypass, the power consumed by the PTR decreases. It can be found from figure 10 that the pressure ratio in the hot end of the regenerator decreases by opening the bypass. This is the main reason that the power consumption decreases with increased opening of the bypass.

CONCLUSION

The effect of the inertance tube on the performance of the miniature pulse tube refrigerator has been demonstrated experimentally. For the miniature PTR, the suitable inertance tube has an inner diameter of about 1.5mm and length of 2m, but the phase shifting effect is small using such a narrow inertance tube. The lowest temperature achieved by the PTR with only an inertance tube as the phase shifter is 107.3K, which is higher than the lowest temperature of 101.6K achieved by the bypass PTR. The miniature PTR with both inertance tube and bypass has the best performance, and it obtains the lowest temperature of 89K. It is also found that the bypass configuration has the function of power recovery.

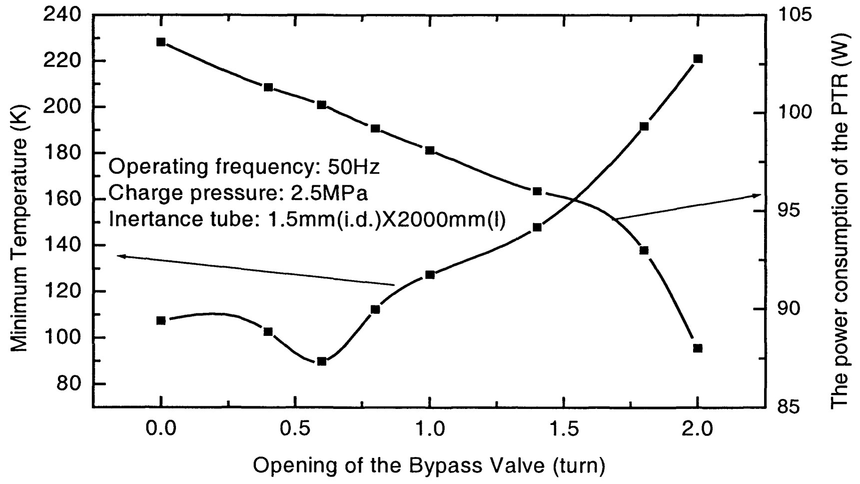

FIGURE 9. The lowest temperature and the power consumption for the inertance and bypass PTR with opening of the bypass valve.

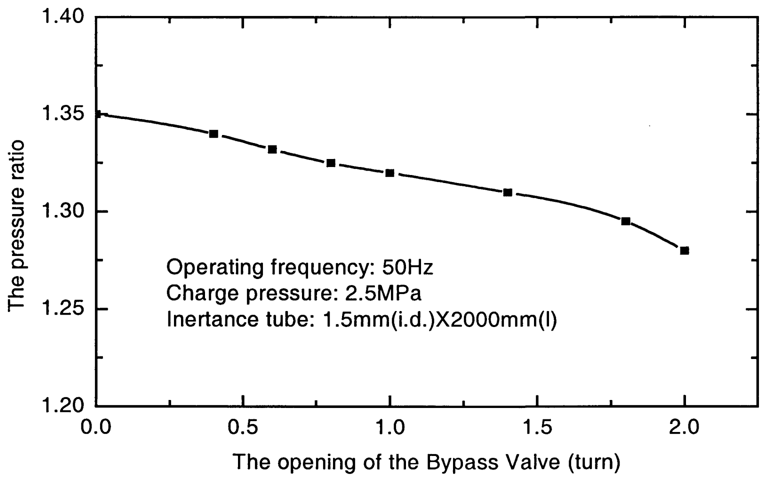

FIGURE 10. The pressure ratio at the hot end of the regenerator with opening of the bypass valve.

REFERENCES

1. Storch Peter J., Radebaugh Ray and Zimmerman James E.. *Analytical Model for the Refrigeration Power of the Orifice Pulse tube Refrigerator.* Boulder: NIST1343, 1990, pp.30-87.
2. Radebaugh R.. "Pulse Tube Cryocoolers for Cooling Infrared Sensors," in *Proceedings of SPIE* Vol.4130, edited by Bjom F.Andresen, et al, 2000, pp.363-379.
3. Kanao,K., Watanabe,N. and Kanazawa,Y., *Cryogenics* **34**, pp.167-170(1994).
4. Harayam T. et al., "Cooling characteristics of a modified miniature pulse tube refrigerator," in *Advances in Cryogenic Engineering*, Vol. 41B, edited by Peter Kittel, Plenum Press, New York, 1996, pp.1427-1435.
5. Zhu S.W., Zhou S.L., Yoshimura N. and Matsubara Y., "Phase shift effect of the long neck tube for the pulse tube refrigerator," in *Cryocooler 9*, edited by R.G.Ross,Jr., Plenum Press, New York, 1997, pp.269-278.
6. Gardner D.L. and Swift G.W., *Cryogenics* **37**, pp.117-121(1997).
7. Ravikumar K.V. and Matsubara Y., "Pulse tube refrigerator based on fluid inertia," in *Advances in Cryogenic Engineering*, Vol. 43B, edited by Peter Kittel, Plenum Press, New York, 1998, pp.1911-1917.
8. Ravikumar K.V. and Matsubara Y., "Experimental results of pulse tube cooler with inertance tube as phase shifter," in *Cryocooler 10*, edited by R.G.Ross,Jr., Plenum Press, New York, 1999, pp.291-298.
9. Duband L., Charles I., Ravex A., "Experimental results on inertance and permanent flow in pulse tube coolers," in *Cryocooler 10*, edited by R.G.Ross,Jr., Plenum Press, New York, 1999, pp.281-290.
10. Marquardt E.D. and Radebaugh R.. "Pulse Tube Oxygen Liquefier," in *Advances in Cryogenic Engieering*, Vol.45A, edited by Shu, et al, New York, Plenum Press, 2000, pp.457-464.
11. Roach Pat R. and Kashani Ali, "Pulse tube coolers with an inertance tube: theory, modeling and practice," in *Advances in Cryogenic Engineering*, Vol. 43B, edited by Peter Kittel, Plenum Press, New York, 1998, pp.1895-1902.