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An inter-phasing Stirling pulse-tube cryocooler without reservoirs

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Abstract

A substantial fraction of the volume of a traditional pulse-tube cryocooler is occupied by a reservoir, which greatly reduces the specific power of the cryocooler. This is undesirable for applications that require a small size and light weight. This paper presents an inter-phasing pulse-tube cryocooler conjoining two or more cold fingers via their inertance tubes. Because the volume flow in the cold fingers are elaborately adjusted to make the total volume flow into the junction of the inertance tubes zero, the reservoirs are allowed to be removed. Experiments demonstrated that, with an electric input power of 1 kW, the cooling power at 77 K reached 59.8 W, corresponding to a relative Carnot efficiency of 16.8%. Compared with a traditional pulse-tube cryocooler, this cryocooler can achieve the same cooling performance.

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Keywords: inter-phasing; pulse tube; cryocooler;

1. Introduction

Stirling pulse-tube cryocoolers are important regenerative cryocoolers which promise high efficiency and high reliability. These are widely used in space, military, telecommunications, etc. To achieve high efficiency, an inertance tube with a reservoir is needed to obtain ideal phase relationship in it (Radebaugh, R.,et al, 2006). The volume of the reservoir is more than ten times greater than the pulse tube, which greatly reduces the specific power of the cryocooler. This is undesirable for space and military applications that require a small size and light weight.

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Much effort has been focused on avoiding using a reservoir. In 1996, Gao used an on-off valve to connect two GM pulse-tube cryocoolers and eliminated the reservoirs (Gao and Matsubara, 1996). But the working mechanism of this configuration is not well revealed (Zhang, et al, 2008; Abhay, et al, 2012). In 2006, Dai used a long inertance tube without a reservoir as the phase shifter in a pulse-tube cryocooler (Dai, et al, 2006). The problem of this method is that a reservoir-less inertance tube cannot offer the necessary impedance in a small pulse-tube cryocooler. In 2012, Wang used the back space of a linear compressor as the reservoir for a pulse-tube cryocooler (Wang, et al, 2012). This method needs a membrane to prevent the DC flow. The gases released by the membrane may contaminate the working gas and hence shorten the cryocooler lifetime.

In this paper, an inter-phasing pulse-tube cryocooler that conjoins two or more traditional pulse-tube cryocoolers will be presented. It eliminates the reservoir and can achieve the same cooling performance as the traditional pulse-tube cryocooler. In the experiment, the cooling power at 77 K reached 59.8 W, corresponding to a Carnot efficiency of 16.8%.

2. Theoretical analysis

In a traditional pulse-tube cryocooler, the reservoir is connected to the inertance tube to enforce a boundary condition of near-zero pressure amplitude. If there is no reservoir or if its volume is not large enough, the inertance tube must be lengthened and the resulting phase shift is smaller. Therefore, the volume should be large enough to make pressure oscillations inside it negligible. Obviously, in an infinitely large reservoir, there are no pressure oscillations, no matter how many inertance tubes are connected to it. Suppose that two inertance tubes are connected to the reservoir, as shown in Fig. 1(a), with volume inflows U_1 and U_2. If the flow amplitudes are equal and their phase difference is 180°, the total mass flow into the reservoir and hence the pressure amplitude are zero, regardless of the reservoir volume. The limiting case of zero reservoir volume is equivalent to having no reservoir at all, with the two inertance tubes connected together directly. The idea can be extended to n inertance tubes as shown in Fig 1(b). Then, the reservoir can also be removed provided that $U_1 + U_2 + U_3 + \cdots + U_n = 0$.

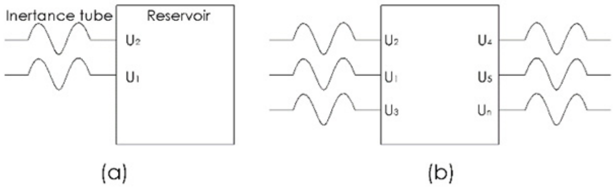

Fig. 1. Analysis of volume flow and pressure in a reservoir

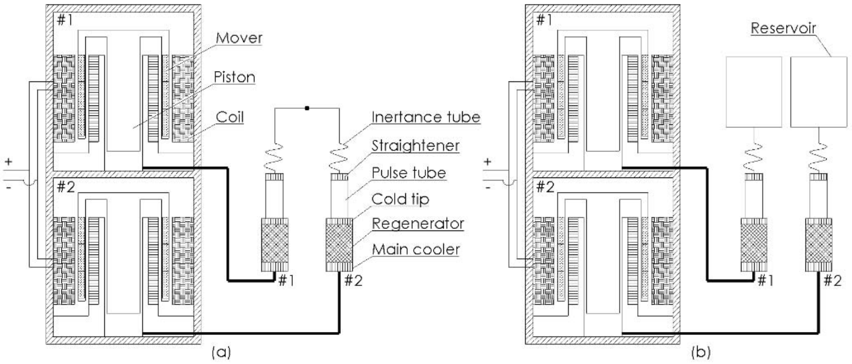

Fig. 2. Schematic of (a) an inter-phasing and (b) a traditional pulse-tube cryocooler

This reasoning inspired us to set up an inter-phasing pulse-tube cryocooler that conjoins n cold fingers without reservoirs. For simplicity, the number of the cold finger is two and the cold fingers are identical as shown in Fig. 2(a). The inertance tubes of the cold fingers are connected. The parameters of the cold fingers are presented in Table 1. Considering a pathway starts from the main cooler inlet of cold finger #1 and ends at the main cooler outlet of cold finger #2, the volume flows in the two main coolers are set the same and in phase. Based on thermoacoustic theory (Swift, 2002), Fig. 3 shows the pressure distribution. It clearly shows that the pressure phase difference in the two cold fingers is approximately 180°. At the inertance tube junction, the pressure amplitude is zero as expected.

Fig. 4 shows the volume flow distributions. The flows in the two main coolers are equal and in phase. Because the two cold fingers are at opposite ends of the pathway, the distribution is perfectly symmetrical. Fig. 5 shows that the pressure and flow are in phase or antiphase in the middle of the regenerators (RG), which implies an ideal phase relationship. The total energy flow distribution indicates that the acoustic power consumed by each compressor is 263.7 W and the cooling power at 77 K is 27 W.

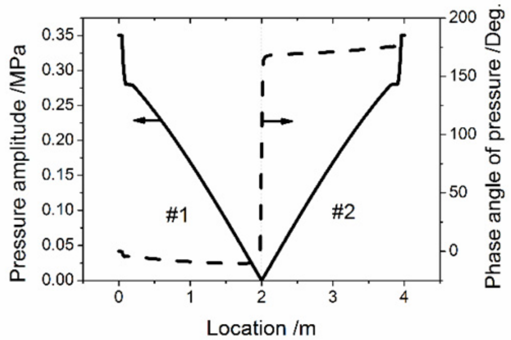

Fig. 3. Pressure distributions in the pulse-tube cryocooler

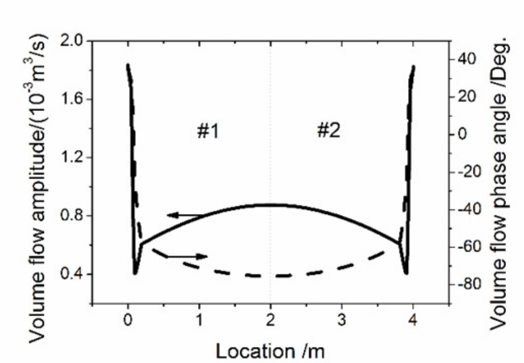

Fig. 4. Volume flow amplitude and phase distributions

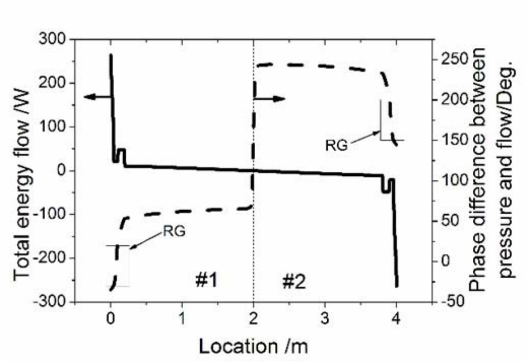

Fig. 5 Total energy flow and phase difference distribution

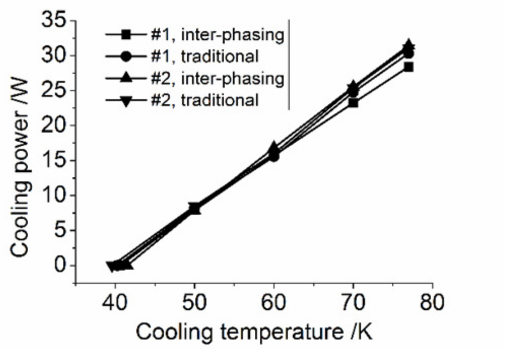

Fig. 6 Temperature dependence of the cooling power

3. Experimental setup and results

The experimental setup follows the design shown in Fig. 2(a), with the main parameters listed in Table 1. The cold fingers are in-line designed. The main coolers are cooled with water at 293 K. The temperature in each cold tip is measured using calibrated platinum (PT100) resistance thermometers to an accuracy of ±0.1 K. A constantan wire heated by a DC voltage source is mounted onto each cold tip to simulate the heating load. The two compressors are placed in series with the same orientation. The currents in the two compressors are in antiphase so that vibrations cancel. The pistons use gas bearing. The input electric power is calculated from the voltage and current data from the compressor, acquired using custom-made software (Labview 7.1, National Instruments, Inc.). For comparison with a traditional pulse-tube cryocooler, two one-litre reservoirs were connected to the inertance tubes, as shown in Fig. 2 (b).

Fig. 6 shows the cooling powers of the two cold fingers with an electric input power of 1 kW, plotted as functions of the cooling temperature. In the inter-phasing configuration, the lowest cooling temperatures of cold fingers #1 and #2 are 40.6 K and 41.5 K, respectively, and the cooling powers at 77 K are 28.4 W and 31.4 W. The Carnot efficiency is 16.8%. In the traditional configuration, the lowest temperatures are 40.3 K and 39.6 K, and the cooling powers at 77 K are 30.3 W and 31.1 W. The two configurations clearly display very similar performances.

Table 1. Main parameters of the cryocooler.

Parameters	Value
Working frequency	75 Hz
Charging pressure	3.5 MPa
Cooling temperature	77 K
Diameter and length of regenerator	⌀30 mm, L45 mm
Diameter and length of pulse tube	⌀16 mm, L80 mm
Inertance tube	⌀4 mm, L1.8 m
Volume of the reservoir	0.001 m^3

4. Conclusion and discussion

An inter-phasing configuration conjoining n cold fingers was introduced to eliminate the reservoirs in Stirling pulse-tube cryocoolers. A viewpoint was presented to understand the function of the reservoirs in pulse-tube cryocoolers and the primary mechanism of this inter-phasing configuration was revealed. An experimental setup consisting of two cold fingers was built to verify the suitability. Theoretical analysis and experimental results show that this inter-phasing pulse-tube cryocooler can achieve the same cooling performance as that of the traditional. It would be helpful to improve the specific power of the pulse-tube cryocooler especially where the cooling load is beyond the capacity of one cold finger as it contains no reservoirs.

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References

Radebaugh, R., Lewis, M., Luo, E. C., 2006. Inertance tube optimization for pulse tube refrigerators. Adv Cryog Eng 51 (A): 59-70.

Gao, J. L., Matsubara, Y., 1996. An inter-phasing pulse tube refrigerator for high refrigeration efficiency. In: Haruyama, T., Mitsui. T., Yamafuji, T., Proceedings of the ICEC 16. Oxford: Elsevier Science, 295-298.

Zhang, X. B., Gan, Z. H., Qiu, L. M., et al, 2008. Computational fluid dynamic simulation of an inter-phasing pulse tube cooler. J Zhejiang Univ Sci A 9 (1): 93-98.

Abhay, S. G., Karunanithi, R., Jacob, S., 2012. Design of twin pulse tube cooler for 3 W @77 K. In: Funaki K, Nishimura A, Kamioka Y, et al. Proceedings of ICEC 24. Fukuoka: Cryogenics and Superconductivity Society of Japan, 387-390.

Dai, W., Hu, J. Y., Luo, E. C., 2006. Comparison of two different ways of using inertance tube in a pulse tube cooler. Cryogenics 46 (4): 273-277.

Wang, X. T., Luo, E. C., Dai, W., et al, 2012. Thermodynamic analysis and experimental verification on a novel looped pulse tube cryocooler. Adv Cryog Eng 57 (B): 1908-1915

Swift, G. W., 2002. Thermoacoustics: A unifying perspective for some engines and refrigerators. ASA Publication, Sewickley PA.