Experimental Investigation on a Single-Stage Stirling-Type Pulse Tube Cryocooler Working below 30 K

J. Ren[1, 2], W. Dai[1], E. Luo[1], X. Wang[1, 2], J. Hu[1]

[1]Chinese Academy of Sciences, Beijing 100190, China;
[2]Graduate University of Chinese Academy of Sciences, Beijing 100049, China

ABSTRACT

Stirling-type pulse tube cryocoolers are promising candidates for space application and for cooling HTS devices. Nevertheless, most single-stage Stirling-type pulse tube cryocoolers (SSPTCs) are unable to reach a cooling temperature below 25 K. In this article, an in-line type SSPTC driven by a linear compressor was designed, fabricated and experimentally investigated. By optimizing the operating conditions, the cryocooler has reached a no-load refrigeration temperature below 34.2 K at 35.2 Hz without the double-inlet phase shifter. However with an optimum double-inlet opening, the cryocooler has reached a no-load refrigeration temperature of 24.7 K and can provide a cooling power of 1.3 W at 30 K when the electric input power to the compressor is 205 W.

INTRODUCTION

Stirling-type pulse tube cryocoolers have the advantages of high efficiency, high reliability and compactness. To date, most applications of Stirling type pulse tube cryocoolers have focused on the temperature region from 40-90 K. The application field could be further extended if a high thermal efficiency at a much lower temperature could be achieved.

In order to obtain a non-zerocooling power below 30 K with reasonable efficiency and reach a much lower temperature, multistage configuration is generally needed.[1-4] Several single stage Stirling-type pulse tube cryocoolers (SSPTCs) for operating temperatures below 30 Khave also been successfully developed. TRW has reported a SSPTC with frequency above 30 Hz, that is able to reach a no-load refrigeration temperature of 29K, and provide a cooling power of 1 W at 35 K with 200 W of electric input power.[5] TIPC has fabricated a single-stage high frequency coaxial pulse tube cryocooler working at 45 Hz that achieves the lowest temperature of about 27 K with a double-inlet valve and cooling powers of 0.2 W/30 K, 0.5W/35 K while consuming 200 W of electrical power.[6]

This article introduces our recent work on an in-line type SSPTC which is running at 35.2 Hz. The cooler can provide a cooling power of over 1.3 W at 30 K when the input electric power is around 200 W. The following will give the details of the configuration and experimental results.

CRYOCOOLER CONFIGURATION

Figure 1 shows the system setup. Optimization of the SSPTC configuration is done through our simulation software[7] based on thermoacoustic theory.[8,9] The design parameters of the SSPTC

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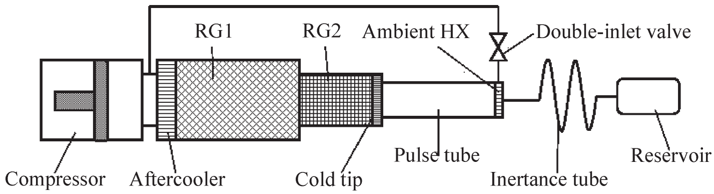

Figure 1. Schematic of the single-stage Stirling-type pulse tube cryocooler.

are summarized in Table 1. The regenerator is optimized by using two sections of different diameters and lengths. The warmer part of the regenerator is filled with 300# (30.7 µm wire diameter) and the colder part was filled with 400# (25 µm wire diameter) stainless steel screens. The phase shifters include an assembly of combined inertance tubes with a 1-litre reservoir, and a double-inlet valve. The flow straighteners at the hot and cold ends of the pulse tube are made from 100-mesh copper screens and 400-mesh stainless stainless-steel screens. The heat from the aftercooler and the ambient heat exchanger is taken away by chilling water whose temperature is contolled by a chiller unit. The charging pressure is set between 2.0~3.0 MPa during the experiments.

The linear compressor made by Zhongke Lihan Inc., China, is a single moving-magnetic motor with a passive counter-balancer. It has a piston diameter of 4 cm. The operating frequency of 35.2 Hz, which is set by the resonance frequency of the balancer, deviates from the optimum operating point. Therefore, the compressor efficiency is only around 60-65%.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 shows a typical cool-down process of the SSPTC, with a charging pressure of 2.5 MPa, a frequency of 35.2 Hz and with the double-inlet valve at best opening. It takes less than 12 minutes to cool down to 40 K and the lowest no-load refrigeration temperature is 24.7 K.The measured pressure ratio is 1.29 at the inlet of the aftercooler and 1.2 at the warm end of the pulse tube. Using a double-inlet configuration leads to a further decrease of the cold-head temperature by 10 K, which indicates that the present inertance tube and the reservoir have not provided the optimum impedance for the cryocooler.

Figure 3 shows the temperature fluctuation at different charging pressures after the SSPTC has worked for over 2 hours. Maximum temperature fluctuations at the two operating conditions are less than 0.2 K, which may be simply due to the intrinsic oscillating gas temperature and relatively small copper cold-head.

Table 1. Details of the SSPTC

Components	Dimensions
1st part of Regenerator	i.d. 25 mm, length 40 mm
2nd part of Regenerator	i.d. 18 mm, length 30 mm
Pulse tube	i.d. 12 mm, length 70 mm
Inertance tube	i.d. 1.5 mm, length 500 mm + i.d. 2.5 mm, length 3000 mm
Double Inlet	adjustable valve with membrane DC-flow suppressor [10]

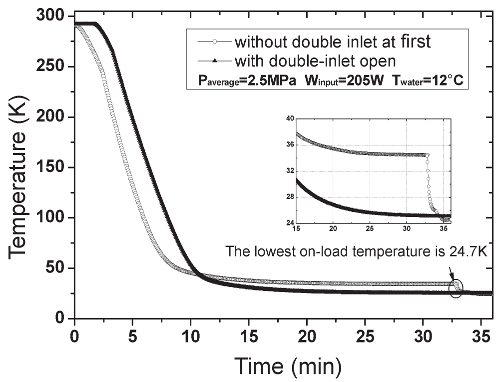

Figure 2. Cool-down process of the SSPTC.

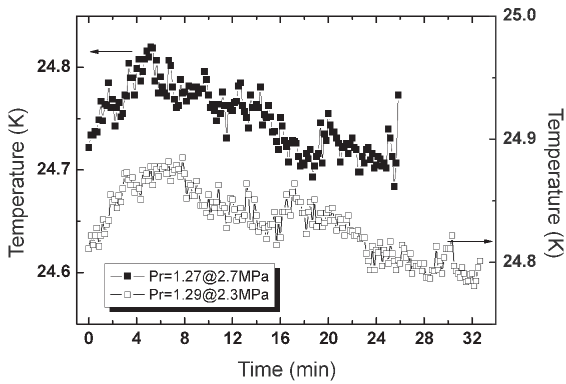

Figure 3. The temperature fluctuation at different charging pressures.

Figure 4 shows the load characteristics of the SSPTC, that is, the variation of the cooling power with refrigeration temperature at different charging pressures. From the figure, it is found that the maximum cooling power of 1.3 W was achieved with 205 W of electric input power at 30 K.The maximum cooling power at 40 K is 3.6 W with 196 W of electric input power. The load characteristics are nearly the same for charging pressures 2.5 MPa and 2.7 MPa, while the electric input power is mainained at about 200 W at 110 V. The results of the lowest pressure 2.3 MPa are a little bit worse because of the lower electric input power which is about 180 W and because the compressor's nominal current is limited due to an impedance mismatch at this charge pressure level.

Figure 5 and 6 show the dependence of the no-load refrigeration temperature on electric input power and cooling water temperature at different charging pressures. The experimental results imply that the SSPTC may achieve lower no-load refrigeration temperature at 2.3 MPa with more input power. The influence of the chilling water at lower temperature to the SSPTC seems comparatively small. The refrigeration temperature decreases by about 1 K when the chilling temperature changes from 22 ºC to 17 ºC, but it only decreases by 0.2 K when the chilling temperature changes from 17 ºC to 12 ºC.

CONCLUSIONS

An in-line type single stage Stirling-type pulse tube cryocooler driven by a linear compressor has been designed and fabricated. The cool-down characteristics of the SSPTC show that s refrigeration temperature of 40 K can be achieved in less than 12 minutes. Without a double-inlet phase shifter, the lowest no-load refrigeration temperature reaches 34.4 K with an electrical input power

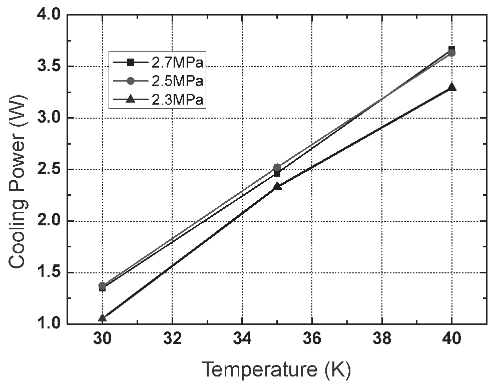

Figure 4. Load characteristics of the SSPTC, variation of the cooling power with refrigeration temperature at different charging pressures.

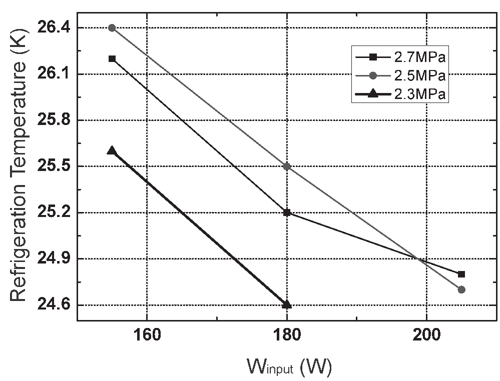

Figure 5. Dependence of the no-load refrigeration temperature on electric power at different charge pressures

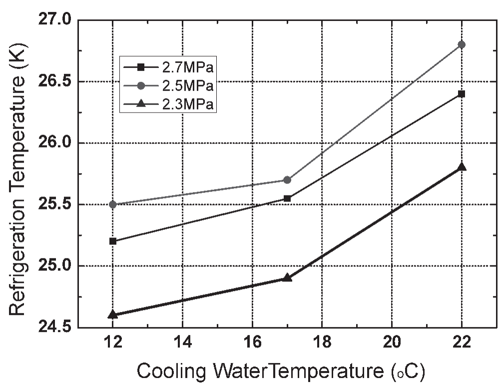

Figure 6. Dependence of the no-load refrigeration temperature on cooling water temperature at different charge pressures.

of 205 W and for a charging pressure of 2.5 MPa. The SSPTC can achieve refrigeration temperature of 24.7 K with the double-inlet valve at its best opening, which delivers 1.3 W of cooling power at 30 K and 3.6 W at 40K, respectively.

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REFERENCES

1. Nast, T.C., et al., "Development of a 4.5 K pulse tube cryocooler for superconducting electronics," *Adv. in Cryogenic Engineering*, Vol. 53, Amer. Institute of Physics, Melville, NY (2008), pp. 881-886.

2. Jaco C, Nguyen T, Raab J, "10K Pulse Tube Cooler Performance Data," *Cryocoolers 15*, ICC Press, Boulder, CO (2009), pp. 1-6.

3. Nast, T.C., et al., Development of Remote Cooling Systems for Low Temperature Spaceborne Systems. *Cryocoolers 14*, ICC Press, Boulder, CO (2007), pp. 33-40.

4. Dietrich, M., Thummes, G., "Two-stage high frequency pulse tube cooler for refrigeration at 25K," *Cryogenics*, Vol. 50, Issue: 4, April 2010, pp. 281-286.

5. Johnson, D.L., Collins, S.A., Heun, M.K., Ross, R.G., Kalivoda, C., "Performance Characteristics of the TRW 3503 and 6020 Pulse Tube Cooler," *Cryocoolers 9*, Plenum Press, New York (1997), pp. 183-193.

6. Yang, L.W., Xun, Y.Q., Thummes, G., Liang, J.T., "Single-stage high frequency coaxial pulse tube cryocooler with base temperature below 30K," *Cryogenics*, Vol. 50, Issue: 5, May 2010, pp. 342-346.

7. Dai, W., Luo, E. C., Zhang, Y., et al, "Detailed Study of a Traveling Wave Thermoacoustic Refrigerator Driven by a Traveling Wave Thermoacoustic Engine," *J. Acoust. Soc. Am.*, 119(5)(2006), pp. 2686-2692.

8. Swift, G.W., "Thermoacoustic engines", *J. Acoust. Soc. Am.*, Vol. 84 (1998), pp. 1145-1180, and, "*Thermoacoustics: A unifying perspective for some engines and refrigerator*". Acoustic Society of America Publications, Sewickley, PA (2002).

9. Xiao, J.H., "Thermoacoustic effects and thermoacoustic theory for regenerative cryocoolers (heat engines)," Ph.D Dissertation, Institute of Physics, Chinese Academy of Sciences (1990) (in Chinese).

10. Hu, J.Y., Luo, E.C., Wu, Z.H., Dai, W., Zhu, S.L., "Investigation of an innovative method for DC flow suppression of double inlet pulse tube coolers," *Cryogenics*, Vol. 47, Issues: 5-6, May-June 2007, pp. 287-291.