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The experimental investigation of a two-stage pulse tube refrigerator

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A two-stage pulse tube refrigerator in combination with a rotary valve and a valved compressor has been constructed. Its performance and the effects of the operating parameters were investigated. A minimum temperature of 11.5 K and a cooling capacity of 1.3 W at 20 K were obtained at a frequency of 4.2 Hz and a system pressure of 1.5 MPa. The 2nd-stage regenerator was only filled with lead shot. © 1996 Elsevier Science Limited

Keywords: two-stage pulse tube refrigerator; experimental investigation

Interest in the pulse tube refrigerator has grown rapidly in recent years because of its merits in terms of mechanical simplicity, high reliability, low vibration and low cost. This type of cryogenic refrigerator has promising application potential in the cooling of infrared devices and sensors, superconducting electronic components, etc.

Developments in recent years have enabled the single pulse tube refrigerator to match the refrigeration capabilities of stirling and G–M refrigerators[1–3]. Many laboratories around the world are engaged in developing multistage pulse tube refrigerators in order to achieve much lower refrigeration temperatures.

Our research group first developed a two-stage orifice pulse tube refrigerator in 1988, which reached a minimum temperature of 31 K[4]. Recently, Tanaka *et al.*[5] achieved a temperature of 15 K with a two-stage pulse tube refrigerator. Matsubara and Gao first obtained the liquid helium temperature (3.6 K) in 1994 with a three-stage pulse tube refrigerator[6] and have recently achieved a lower temperature of 2.9 K[7]. Bradley and Radebaugh[8] obtained a temperature of 10.5 K with a three-stage pulse tube. However, the working performance of these pulse tube refrigerators in the lower temperature range is weak, and the efficiency of multistage pulse tube refrigerators needs to be further increased.

In this paper, the performance of a two-stage pulse tube refrigerator constructed by the authors was studied. A special rotary valve was made for a valved pulse tube system and its performance was satisfactory.

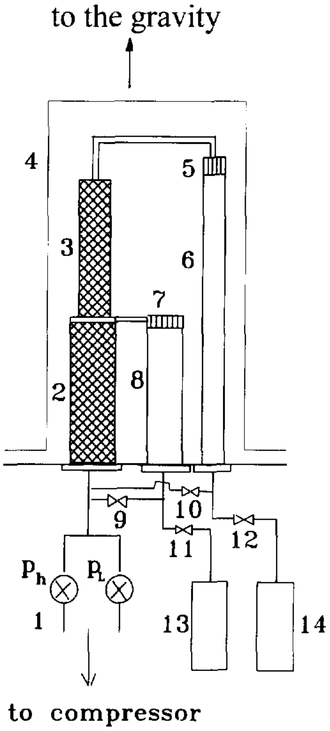

Figure 1 Configuration of experimental apparatus: 1, compressor; 2, 1st-stage regenerator; 3, 2nd-stage regenerator; 4, vacuum chamber; 5, 2nd-stage cold head; 6, 2nd-stage pulse tube; 7, 1st-stage cold head; 8, 1st-stage pulse tube; 9,10, double-inlet valve; 11,12, orifice valve; 13,14, reservoir

Experimental apparatus

The configuration of the experimental apparatus is shown in *Figure 1*. The pressure oscillation was generated by a valved helium compressor commonly used for G–M cryocoolers. The compressor was connected to the 1st-stage regenerator hot end by a rotary valve. The input power for the compressor used in the experiment was about 2.5 kW, while the calculated isothermal work required for this refrigerator was about 1 kW. The pulse tubes and regenerators were made of stainless steel of wall thickness 0.25 mm, and their dimensions are given in *Table 1*.

The cold head of the 2nd-stage pulse tube was 12 mm in length and its inner diameter was 9.6 mm. The hot ends of the pulse tubes had no heat exchangers and were cooled with air by natural convection. The characteristic of this construction was that the 1st- and 2nd-stage pulse tube extended into the room temperature region at the cold end. By using the configuration suggested in reference 6 for the multi-stage pulse tube refrigerator, a lower refrigeration temperature at the last stage can be reached since the enthalpy flow in the pulse tube is released to the room temperature end without using the cooling power of the upper stage. A reservoir of 300 cm^3 volume was connected to the pulse tube hot end of each stage through a needle valve and a double-inlet valve was used between the hot ends of the pulse tube and the regenerator for each stage; the orifice valve and the double-inlet valve are adjustable needle valves. A Rh–Fe thermometer was used to measure the temperature of the 2nd-stage pulse tube cold head. The measuring current was supplied by a DC power source made by Lakeshore Co. Eight copper–constantan thermocouples were used to measure the wall temperature of the pulse tube and the regenerator. The pressure wave at the outlet of the rotary valve was measured with a pressure sensor.

For a valved pulse tube system, the performance of the rotary valve has direct effects on the refrigeration performance of the pulse tube refrigerator. A special rotary valve for the pulse tube refrigerator was designed and constructed. The latest model of this rotary valve is shown in *Figure 2*. Tests on the valve were satisfactory. The typical pressure wave measured is shown in *Figure 3*. In the present study, the refrigeration temperature was lowed to 11.5 K from 14.5 K by using this rotary valve with the same pulse tube structure and operating parameters.

Results and discussion

At first, the refrigerator performance of the double-inlet version was compared with that of the conventional orifice version. *Table 2* shows the effect of the 1st-stage double-inlet valve on the cold-head temperature. It was found that the temperature of the 1st-stage cold head decreased when the 1st-stage double-inlet valve was opened, while the temperature of the 2nd-stage cold head did not vary, as seen in *Table 2*. However, the cold-head temperature of the 2nd-stage pulse tube decreased greatly when the 2nd-stage dou-

Table 1 Dimensions of pulse tubes and regenerators

Component	Materials	ID (mm)	Length (mm)
1st-stage regenerator	SS tube filled with 250–350 mesh SS and phosphor bronze screens	32	120
2nd-stage regenerator	SS tube filled with 217 g lead shot and 350 mesh SS screens	17	150
1st-stage pulse tube	SS tube	19	120
2nd-stage pulse tube	SS tube	9	386

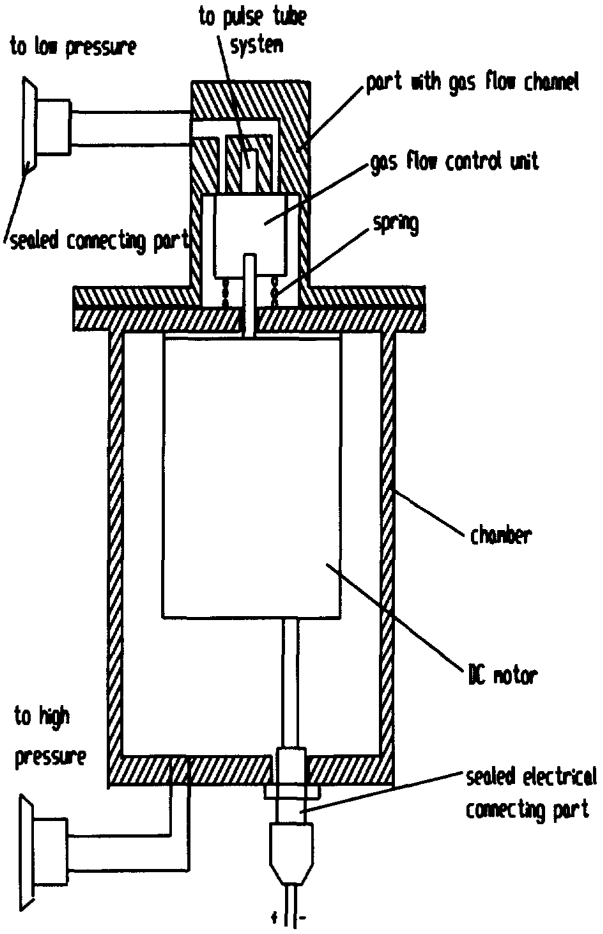

Figure 2 Configuration of rotary valve

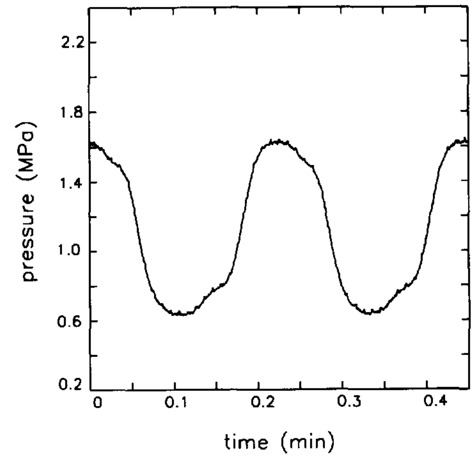

Figure 3 Typical pressure wave measured at rotary valve outlet

Table 2 Effect of 1st-stage double-inlet valve on cold-head temperature

Opening degree of 1st-stage double-inlet valve (turns)	1st-stage cold head temperature (K)	2nd-stage cold head temperature (K)
0	66	14.4
1.3	62	14.4

Operating frequency 4.2 Hz, system pressure 1.5 MPa

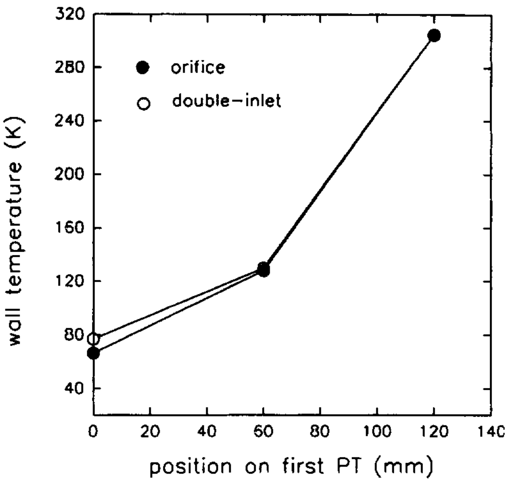

Figure 4 Wall temperature distribution on 1st-stage pulse tube (f = 4.2 Hz, Pa = 1.5 MPa)

ble-inlet valve was opened. The 2nd-stage cold-head temperature was 28.4 K with the single inlet version and 11.5 K with double-inlet version (see *Figures 4* and *5*). Thus, only the 2nd-stage double-inlet version had a positive effect on the performance of our two-stage pulse tube refrigerator. This result may not be the same for two-stage pulse tube refrigerators.

The following results were obtained when the 2nd-stage double-inlet valve was opened and the 1st-stage double-inlet valve was closed.

The influences of the 2nd-stage double-inlet valve on the wall temperature of the 1st and 2nd stage pulse tubes are shown in *Figures 4* and *5*, respectively. The 2nd-stage double-inlet valve greatly affected the temperature on the wall of the 2nd-stage pulse tube. There is a maximum temperature in the middle for the double-inlet version. Half of the 2nd-stage pulse tube was worked above room temperature. Therefore, removing the heat in the 2nd-stage pulse tube is the key to improving the performance of the multi-stage pulse tube refrigerator. Additional analysis of this phenomena will be given in *Figure 8*. It can be seen from *Figure 5* that the 1st-stage cold-head temperature increased somewhat when the double-inlet valve was opened.

The cold-end temperature of the 1st-stage regenerator increased and that of the 2nd-stage regenerator decreased

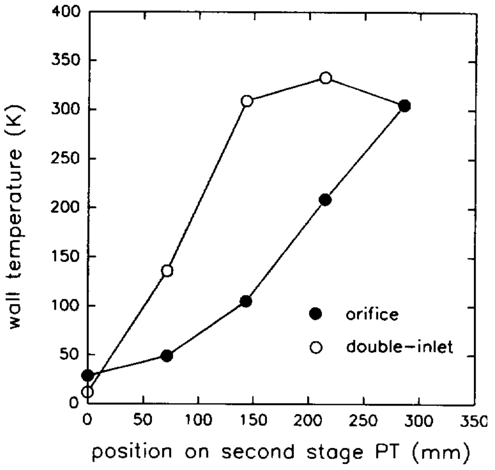

Figure 5 Wall temperature distribution on 2nd-stage pulse tube (f = 4.2 Hz, Pa = 1.5 MPa)

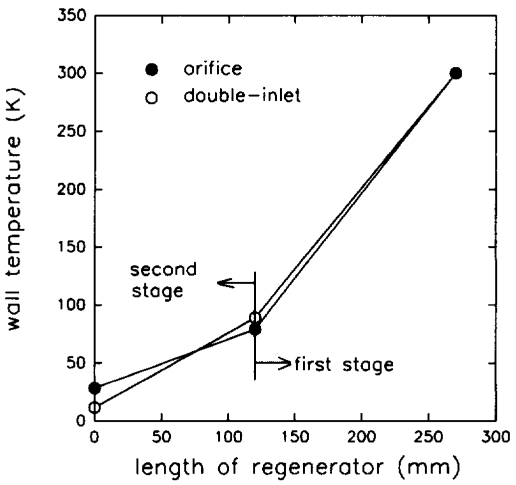

Figure 6 Wall temperature of 1st-stage and 2nd-stage regenerator (f = 4.2 Hz, Pa = 1.5 MPa)

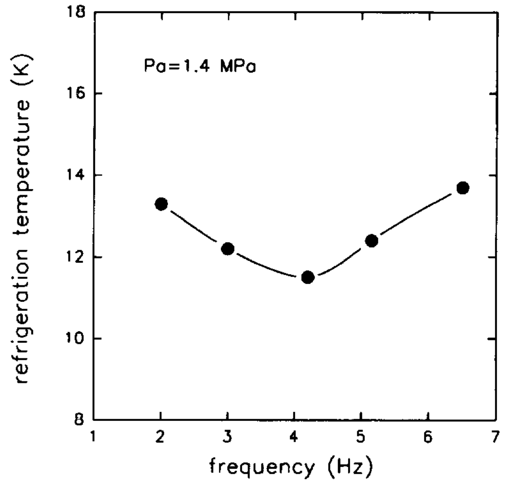

Figure 7 Variation in 2nd-stage cold-head temperature with frequency

when the double-inlet valve was opened, as can be seen in *Figure 6*.

Variation in the 2nd-stage cold-head temperature with operating frequency is shown in *Figure 7*. The lowest temperature of 11.5 K on the cold head was achieved at an optimum frequency of 4.2 Hz. At present, it is the lowest temperature ever obtained with a two-stage pulse tube refrigerator.

The influence of the system pressure on the performance of the pulse tube refrigerator is shown in *Table 3*. It can be seen that a higher system pressure leads to a slightly lower refrigeration temperature. The present authors consider that this result may be caused mainly be the gas temperature increasing in the 2nd-stage pulse tube with increas-

Table 3 Effects of system pressure on refrigerator performance

System pressure (MPa)	P_h (MPa)	P_L (MPa)	Lowest temperature (K)
1.3	1.35	0.38	11.7
1.5	1.58	0.38	11.5

P_h is discharging pressure of compressor, P_L is absorbing pressure of compressor

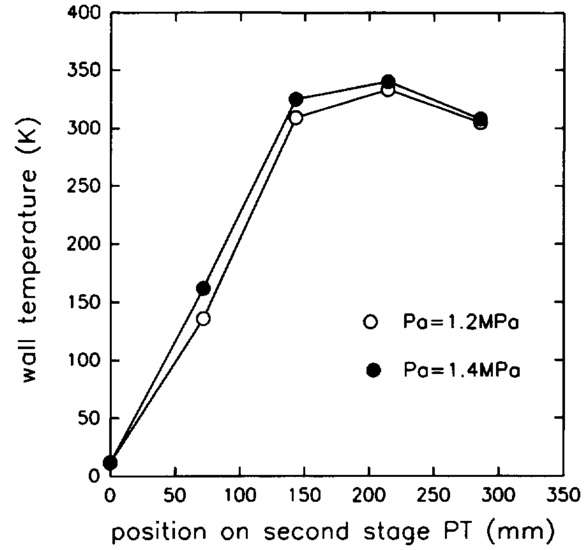

Figure 8 Effects of system pressure on wall temperature distribution on 2nd-stage pulse tube

ing pressure (see *Figure 8*). The regenerative tube of Matsubara and Gao[6] was used to improve the performance of the 2nd-stage pulse tube. However, a better result was obtained with an empty tube by these same authors[7]. Therefore, it is necessary to further explore the refrigeration mechanism to find an effective way of improving the 2nd-stage pulse tube operation and hence the efficiency of multi-stage pulse tube refrigerators.

Figure 9 shows the cooling capacity on the 2nd-stage cold head. A minimum temperature of 11.5 K and a 1.3 W heat capacity at 20 K were achieved by this two-stage pulse tube refrigerator with a system pressure of 1.5 MPa and operating frequency of 4.2 Hz. The 1st-stage cold-head temperature increased slightly when the cooling load was added to the 2nd-stage cold-head. *Figure 10* shows the cooling capacity on the 1st-stage cold head. A cooling power of 1 W for a 5 K temperature rise was obtained in the experiment.

The cooling-down curves for the two cold heads are shown in *Figure 11*. It took about 80 min to reach the lowest temperature.

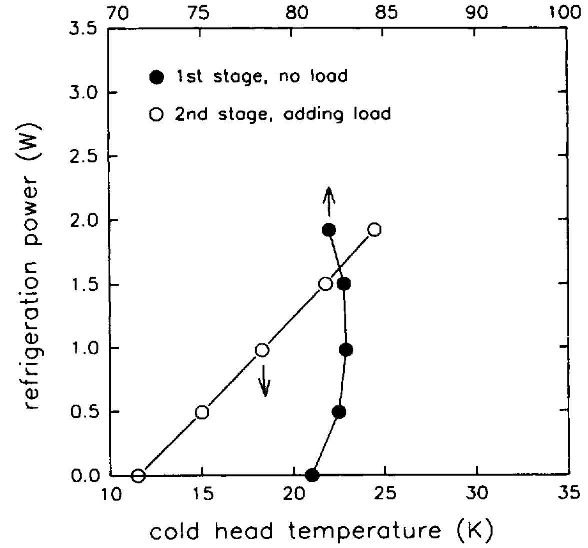

Figure 9 The cooling capacity on 2nd-stage cold head (f= 4.2 Hz, Pa = 1.5 MPa)

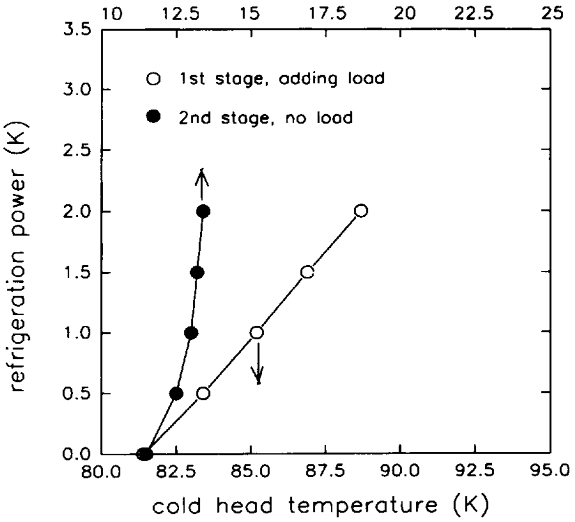

Figure 10 Cooling capacity on 1st-stage cold head (f= 4.2 Hz, Pa = 1.5 MPa)

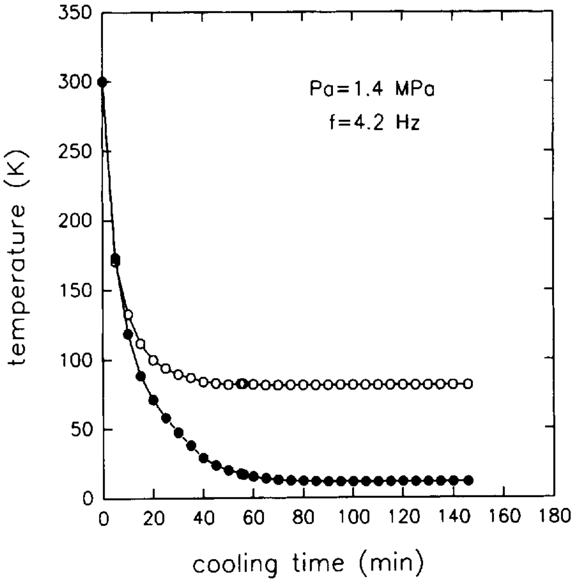

Figure 11 Cooling-down curves for the two cold heads (f= 4.2 Hz, Pa = 1.5 MPa)

The efficiency of the 2nd-stage regenerator, which worked in the above temperature range, was not satisfactory in the present study since it was only filled with lead shot. Better performance of the two-stage pulse tube refrigerator is expected by using magnetic regenerative materials for the 2nd-stage regenerator and improving the configuration of the two-stage pulse tube refrigerator.

Conclusions

A two-stage pulse tube refrigerator in combination with a rotary valve and a valved compressor was constructed and its working characteristics were investigated. A minimum temperature of 11.5 K and a cooling capacity of 1.3 W at 20 K were obtained at an operating frequency of 4.2 Hz and a system pressure of 1.5 MPa.

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References

1 **Wang, C., Cai, J.H., Zhu W.X. and Zhou, Y.** Miniaturization of a co-axial pulse tube cooler and linear motor drive compressor, paper presented at CEC/ICMC (1995)

2 **Chan, C.K.** Overview of cryocooler technologies for space-based electronics and sensors *Proc 1989 Cryogenic Engineering Conference* (1990) 1239

3 **Zhou, Y. and Yan, H.** Pulse tube refrigerator research. *Proc 7th Int Cryocooler Conf* Santa Fe (1992)

4 **Zhou, Y., Zhu, W.X. and Liang, J.T.** Two stage pulse tube refrigerator *Proc 5th Int Cryocooler Conf* Monteray, CA (1988) 137

5 **Tanaka, M., Nishitani, T., Kodama, T., Kawaguchi, E. and Yanai, M.** Experimental and analytical study of two stage pulse tube refrigerator, paper presented at CEC/ICMC (1995)

6 **Matsubara, Y. and Gao, J.L.** Novel configuration of three-stage pulse tube refrigerator for temperatures below 4 K *Cryogenics* (1994) **34** 259

7 **Tanoda, K., Gao, J.L., Yoshimura, N. and Matsubara, Y.** Three-stage pulse tube refrigerator controlled by four valve method, paper presented at CEC/ICMC (1995)

8 **Bradley, P.E. and Radebaugh, R.** A three stage pulse tube refrigerator for temperature near 4 K, paper presented at CEC/ICMC (1995)