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Experimental research on 2 stage GM-type pulse tube refrigerator for cryopump

Seong-Je Park[*], **Jun-Seok Ko, Yong-Ju Hong, Hyo-Bong Kim, Han-Kil Yeom, Deuk-Yong Koh**

Energy Systems Research Division, Korea Institute of Machinery & Materials

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***Abstract*-- The experimental results of the 2 stage Gifford-McMahon(GM) type pulse tube refrigerator (PTR) for cryopump are presented in this paper. The objectives of this study are to develop design technology of the integral type 2 stage PTR which rotary valve is directly connected to the hot end of the regenerator and acquire its improved performance. Design of the 2 stage PTR is conducted by FZKPTR(Forschungs Zentrum Karlsruhe Pulse Tube Refrigerator) program for the design of pulse tube refrigerators. The fabricated PTR has U-type configuration and incorporates orifice valve, double-inlet valve and reservoir as phase control mechanism. Rotary valve is used to make pulsating pressure and is directly connected to inlet of 1st stage regenerator. From experiments, cooling performance map and pressure waveform at each point were measured for different operating frequencies. Experimental results show the best cooling performance with 2 Hz operation in spite of small pressure amplitude. The lowest temperatures of the 2 stage PTR were 16.9 K at the second stage and 58.0 K at the first stage. The cooling capacities achieved were 14.4 W at 79 K, the first stage and 3.6 W at 29 K, the second stage.**

1. INTRODUCTION

The pulse tube refrigerator (PTR) is a small scale cryocooler which was invented by Gifford and Longsworth in 1963. The pulse tube refrigerator, which has no moving parts at its cold section, is attractive in obtaining higher reliability, simpler construction, and lower vibration than any other small refrigerator. The cooling performance of the PTR has been improved since 1990s and it can be a good candidate for substitution of Gifford-McMahon (GM) cryocooler or Stirling cryocooler [1, 2].

So far PTR have been believed that it has lower efficiency than a comparable Stirling, and GM cryocooler. However, now the pulse tube process is understood as a Stirling process. With this understanding, there are no physical reasons for having lower efficiency with a properly designed PTR. In the past few years, these have been verified for compact single-stage Stirling-type PTRs[3] and also for GM-type PTRs[4]. Multi-stage GM-type PTRs below 2 K are being developed.[5, 6]

A commercial cryopump uses 2 stage GM cryocooler. The 1st stage cold-end cools the 1st cryoarray and radiation shield and the 2nd stage cold-end cools the 2nd cryoarray.

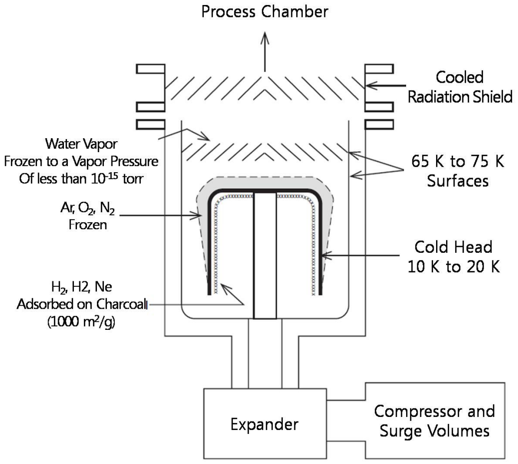

Fig. 1. Typical configuration of cryopump [2] .

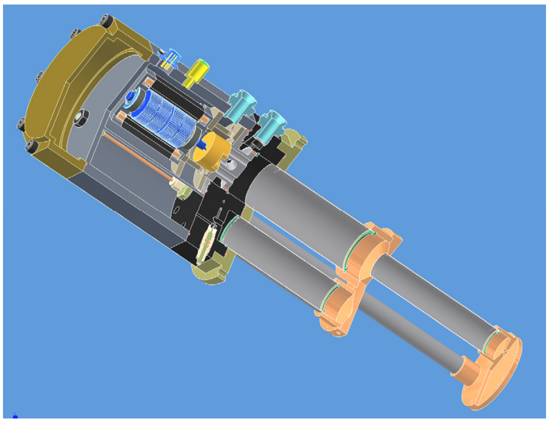

Fig. 2. Conceptual model of PTR for commercialization.

Fig. 1 shows a typical configuration and principle of cryopump. Water vapor and carbon dioxide are trapped at the 1st cryoarray. Argon, nitrogen, oxygen can be condensed at the 2nd cryoarray. But helium, hydrogen and neon cannot be condensed near 20 K because they have high vapor pressure at that temperature. They can be removed from the space by cryosorption. The porous material like as activated carbon is attached to the 2nd cryoarray and adsorbs gases. Typically, cooling capacities of the cryopump have 35 ~ 55 W at 80 K for the first stage and 5 ~ 10 W at 20 K for the second stage.

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[*] Corresponding author: sjpark@kimm.re.kr

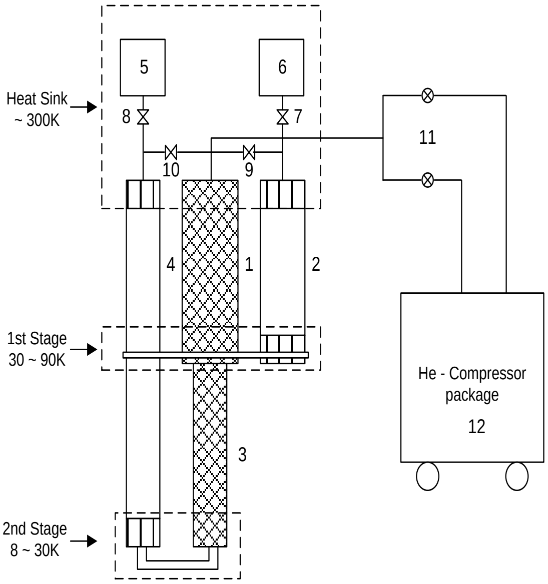

Fig. 3. Schematic diagram of 2 stage pulse tube refrigerator: 1. 1st stage regenerator, 2. 1st stage pulse tube, 3. 2nd stage regenerator, 4. 2nd stage pulse tube, 5,6. reservoir 7,8. orifice valve, 9,10. double inlet valve, 11. rotary valve, 12. He compressor.

Fig. 2 is the conceptual model of PTR for commercialization. All parts including rotary valve, heat exchangers and phase control devices are integrated in one module. Before developing the commercial model, we developed the pre-commercial model in which the rotary valve is directly connected to the inlet of 1st regenerator and the commercial metering valve is used for phase control.

In this paper, research is focused on a 2 stage GM-type PTR with 3.8 kW input power compressor for cryopump application. And we will describe temperature variation with valve opening of orifice and double inlet at the single-stage and 2 stage PTR. Also cooling capacities of 2-stage PTR at the first stage, 80 K and at the second stage, 20 K will be measured.

2. EXPERIMENTAL APPARATUS

2.1. Fabrication of PTR

The 2 stage pulse tube refrigerator was fabricated and tested as shown in Fig. 3. The fabricated PTR consists of a helium compressor, regenerators, pulse tubes, heat exchangers, reservoirs, orifice valves, double inlet valves and rotary valve.

PTR was designed by using FZKPTR and its specifications are shown in Table 1. FZKPTR is the numeric code based on the thermoacoustic theory for analysis and design of the small scale cryocooler, it proved to be a valuable tool for doing such work.

Orifice valves, double-inlet valves and reservoirs are used as phase control devices. For an orifice valve which is drawn with one valve in Fig. 3, two metering valves are connected in opposite direction to suppress the flow imbalance because the used metering valve shows different opening at the same turning due to its configuration. The metering valve has 0.03 of flow coefficient and full opening is 9 turns. For the application to cryopump, the cold-end of PTR should be the appropriate configuration which the radiation shield and cryoarray can be mounted, but the cold ends of the regenerator and pulse tube were connected by using copper tube in this study. In the future study, we will improve the structure of the cold ends as shown Fig. 2.

TABLE I
SPECIFICATIONS OF FABRICATED PTR.

	1st stage	**2nd stage**
Regenerator	O.D. = 50.8 L = 175 t = 0.4	O.D. = 25.4 L = 150 t = 0.3
Regenerating material	#200 Phosphorous bronze mesh	Pb ball (Dia. = 150 mm)
Pulse tube	O.D. = 38.1 L = 175 t = 0.38	O.D. = 19.05 L = 300 t = 0.3
*Orifice valve	Swagelok metering valves (M series) Max. Cv = 0.030	
*Double-inlet valve	Swagelok metering valve (S series) Max. Cv = 0.004	
Reservoir	1 L	

* Same components were used at 1st and 2nd stage for orifice valve, double-inlet valve and reservoir.

In the fabricated PTR, the first stage regenerator is filled with phosphor bronze meshes. The second stage regenerator is filled with lead shot balls which have been used in GM cryocoolers. The brass meshes are also stacked at the cold end of pulse tube for flow straightening and heat exchange. Silicon diode sensors are used to measure the cold-end temperature.

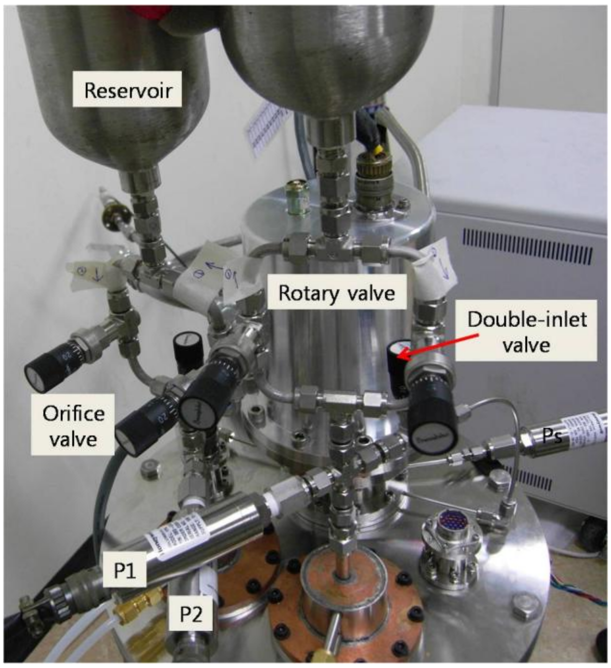

Fig. 4. Photo of experimental setup.

Rotary valve to generate pulsating pressure was directly connected to the inlet of 1st stage regenerator to minimize pressure loss and compliance effect through connection part(Fig. 4). The material of rotor and stator of rotary valve is vespel and SUS 316, respectively. And, rotary valve is driven by stepping motor (PK2913-02A, Oriental motor).

2.2. Experimental Setup

Fig. 4 shows the experimental setup in this study. The cold part of PTR is vacuum insulated during operation. Three pressure sensors are installed at the inlet of 1st stage regenerator (Ps), the warm side of 1st stage pulse tube (P1) and the warm side of 2nd stage pulse tube (P2) to measure pressure waveform during operation.

Helium compressor (HC-70, Genesys) used in the experiment have 3.8 kW of rated electric power and can generate flow rate of 70 SCFM (Standard ft^3/min). Generally, the flow rate of helium compressor is affected by the load condition such as the configuration of connected PTR, operating conditions and cold-end temperature.

3. RESULTS AND DISCUSSION

3.1. No-load Test

In the experiment, charging pressure is 1.6 MPa. No-load test was performed with 2 Hz of operating frequency. For several pairs of opening of phase control valves, temperature of 1st stage cold-end (T1) and that of 2nd stage cold-end (T2) were measured.

Table 2 shows the results of no-load test. From results of case 3 ~ 6, T2 is sensitive to the opening of 2nd stage orifice valve. When 2nd stage orifice valve is closed (case 5), T2 is higher than T1 and it means that 2nd stage PTR does not working as a cooler. In case 5, temperature of 1st stage does not seem to be much low although the distributed flow to 2nd stage would be minimized.

Fig. 5 shows pressure waveforms measured at several points of PTR. Pressure at the inlet of 1st regenerator (Ps) oscillates well without significant pressure loss between the supply pressure (PH) and return pressure (PL) of helium compressor. But, the small pressure amplitudes of Ps, P1, P2 result in the low cooling performance of the fabricated PTR.

3.2. Cooling Capacity

From the results of no-load test, the valve opening of case 8 shows the best cooling performance. With same valve opening, heat load tests were performed using electric heating wire (Nichrome wire) which is wrapped around the cold-end of each pulse tube. Generally, GM-type PTR operates at 1 to 2 Hz of operating frequency and thus we selected three different frequencies of 1.50, 1.75, 2.00 Hz. For the selected frequencies, tests were performed for 4 cases of heat load condition and the cooling performance maps are shown in Fig. 6. The decrease of cooling performance was observed for the operating frequency over 2 Hz. The fabricated PTR shows the best cooling performance at the 2 Hz of operating frequency. In this case, cooling capacities were 14.4 W at 79 K, the first stage and 3.6 W at 29 K, the second stage.

Table 3 shows the pressure amplitude at the inlet of 1st regenerator (Ps) with operating frequency and heat load in the 1st and 2nd cold end. As the heat loads in the 1st and 2nd

TABLE II
EXPERIMENTAL RESULTS OF NO-LOAD TEST.

Case	Valve turn*	T1**, K	T2**, K
1	(4, 4, 2, 2, 0, 0)	55.24	28.57
2	(4, 4, 2, 2, 12, 6)	55.92	22.78
3	(5, 5, 2, 2, 0, 0)	56.96	28.66
4	(5, 5, 3, 3, 0, 0)	53.61	50.19
5	(5, 5, 0, 0, 0, 0)	48.48	72.18
6	(5, 5, 1, 1, 0, 0)	55.27	26.73
7	(5, 5, 1, 1, 6, 12)	57.71	18.96
8	(4, 4, 2, 2, 6, 12)	57.89	17.80

* Valve turn = (OP1-1, OP1-2, OP2-1, OP2-2, DI1, DI2)
OP = orifice valve, DI = double-inlet valve
** T1, T2 = Temperature of 1st and 2nd cold-end, respectively

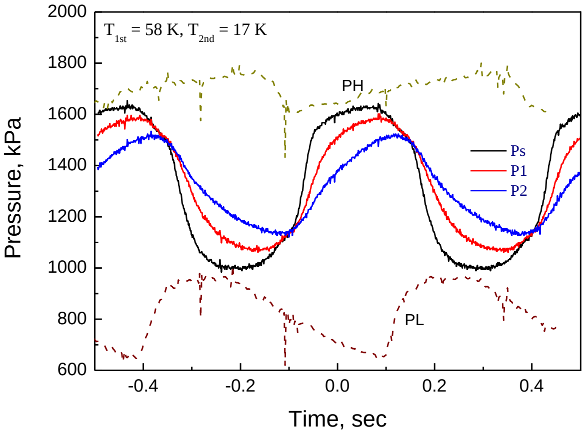

Fig. 5. Measurement of pressure waveforms: PH. supply of compressor, PL. return of compressor, Ps. inlet of 1st regenerator, P1. warm end of 1st pulse tub, P2. warm end of 2nd pulse tube(2Hz no load condition).

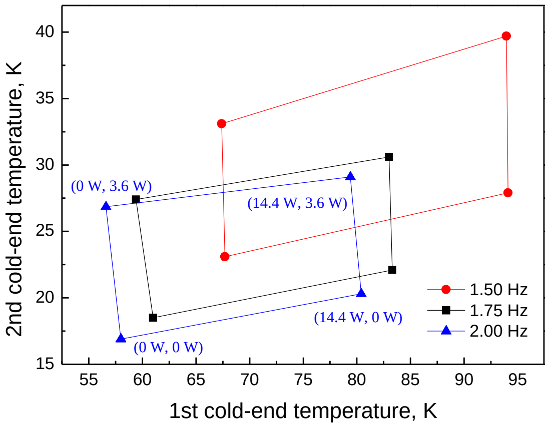

Fig. 6. Cooling performance map for 1.50, 1.75, 2.00 Hz of operating frequency with same heat load condition.

cold end increase, amplitude of pressure wave increases together. It means that mean pressure of the PTR increases with temperature of the 1st and 2nd cold end.

Also this can be explained that cooling capacity per unit mass flow through the regenerator is improved by the increase of the pressure amplitude.

Fig. 7 shows the pressure amplitude of Ps as operating frequency and heat load conditions. Obviously, pressure amplitude becomes smaller as operating frequency increase because a compliance effect of PTR increases. This phenomenon results from the increase of compliance effect of PTR. The compliance effect is proportional to operating frequency and inversely proportional to temperature. The lower temperature and higher operating frequency makes the larger compliance effect and the smaller pressure amplitude.

In the PTR, the expansion PV work produces a cooling effect of cooler. The cooling power per cycle is proportional to the amplitude of pressure and mass flow rate at the cold-end and the degree of in-phase. The cooling capacity is the product of the cooling power and operating frequency.

From results, operating frequency of 2 Hz shows the best cooling capacity. In this case, cooling capacities were 14.4 W at 79 K for 1st stage and 3.6 W at 29 K for 2nd stage. In general, cooling capacities for cryopumps depend on their specification and design. The target cooling capacities were 5 W at 20 K and 35 W at 80 K for 1st and 2nd stage, respectively. These values are for a good cool-down time and vacuum level in medium size ICP 200 cryopump.

In this paper, we directly connected rotary valve to the hot end of 1st stage regenerator to minimize pressure loss and compliance effect through connection part. So Peak to peak of the pressure amplitude at the inlet of 1st regenerator increased, cooling performance was improved. But the results of the cooling capacities from Table 3 were not enough for cryopump application. To get the larger capacities, diameter, length and valve opening of pulse tube and regenerator at the first stage and the second stage should be optimized and the dead volume of connecting tube at the orifice valves, double inlet valves and buffers should be minimized, also. Especially, the compliance effect of 1st regenerator and 1st pulse tube seem to be large.

TABLE III

AMPLITUDE OF PRESSURE WAVE (PS).

Freq.	Heat load (1st, 2nd)	T1 (K)	T2 (K)	*Pk-Pk of Ps (kPa)
1.5 Hz	0, 0	67.7	23.1	734.3
	0, 3.6	67.4	33.1	772.2
	14.4, 0	94.1	27.9	844.0
	14.4, 3.6	94.0	39.7	886.7
1.75 Hz	0, 0	61.0	18.5	664.2
	0, 3.6	59.4	27.4	681.5
	14.4, 0	83.3	22.1	762.1
	14.4, 3.6	83.0	30.6	782.2
2.00 Hz	0, 0	58.0	16.9	630.7
	0, 3.6	56.6	26.9	639.1
	14.4, 0	80.4	20.3	717.2
	14.4, 3.6	79.4	29.1	733.9

* Peak to peak valve of pressure waveform (Ps)

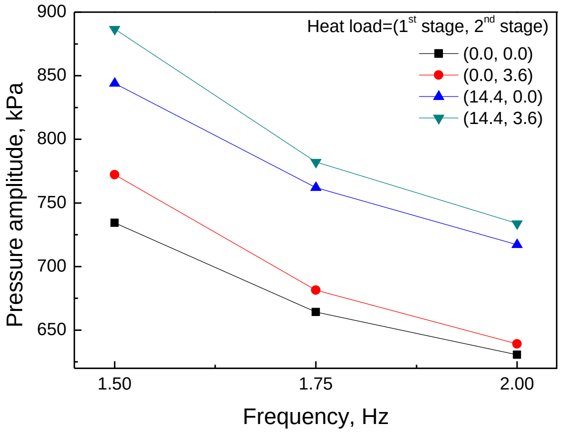

Fig. 7. Pressure amplitude of Ps.

This is inferred from the small pressure amplitude and the less sensitivities of 1st stage orifice valve than 2nd stage orifice valve on the cooling performance of PTR.

4. SUMMARY

We have undertaken experimental researches about no load temperature with valve turn, cooling performance map and pressure waveform with different operating frequency and heat load in the 1st and 2nd cold end.

Following conclusions are drawn from the experimental results.

(1) In the 2 stage PTR, temperature of the 2nd stage is sensitive to the opening of 2nd stage orifice valve.

(2) The compliance effect in the PTR is proportional to operating frequency and inversely proportional to temperature. The lower temperature and higher operating frequency makes the larger compliance effect and thus, the smaller pressure amplitude.

(3) The cooling performance with the opening of the orifice valve and double inlet valve has been experimentally investigated for 2 stage PTR. The optimization of pressure ratio, length of pulse tube and regenerator has not been carried out yet. However, the lowest temperature of a 2 stage PTR operating at room temperature reaches 16.9 K at the second stage and 58.0K at the first stage. The cooling capacities achieved were 14.4 W at 79 K, the first stage and 3.6 W at 29 K, the second stage.

For cryopump application, the minimum temperature at second stage should be less than 10 K to get enough cooling power. It is necessary to increase regenerator performance and to decrease pulse tube losses at each stage. Moreover pulse tube refrigerator optimization with valve opening at each stage should be followed.

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