Performance improvement of 2 stage GM-type pulse tube Cryocooler for cryopump

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Abstract-- This paper describes experimental study and performance improvement of 2 stage Gifford-McMahon (G-M) type pulse tube cryocooler for cryopump. The objective of this study is to improve the efficiency of 2 stage pulse tube cryocooler for substituting 2 stage G-M cryocooler used in cryopump. The target cooling capacities are 5 W at 20 K and 35 W at 80 K for the 1st and the 2nd stage, respectively. These values are good cooling capacities for vacuum level in medium size ICP 200 cryopump. Design of the 2 stage pulse tube cryocooler is conducted by FZKPTR(Forschungs Zentrum Karlsruhe Pulse Tube Refrigerator) program. In order to improve the performance of 2 stage pulse tube cryocooler, U-type pulse tube cryocooler is fabricated and connecting tubes are minimized for reducing dead volumes and pressure losses. Also, to get larger capacities, orifice valves and double inlet valves are optimized and the compressor of 6 kW is used. On the latest unit, the lowest temperatures of 2 stage pulse tube cryocooler are 42 K (1st stage) and 8.3 K (2nd stage) and the cooling capacities are 40 W at 82.9 K (1st stage) and 10 W at 20.5 K (2nd stage) with 6.0 kW of compressor input power. This pulse tube cryocooler is suited for commercial medium size cryopump. In performance test of cryopump with 2 stage pulse tube cryocooler, pumping speed for gaseous nitrogen is 4,300 L/s and the ultimate vacuum pressure is 7.5×10^{-10} mbar.

1. INTRODUCTION

The cryopump provides ultra clean vacuum and has very high pumping speed for water vapor and hydrogen gas as well as for other gases. In general, the cryopump has used the 2 stage G-M cryocooler in order to cool the cryopanel.

In some semiconductor equipments, a vibration is very critical parameter in design. And an isolator has been used to reduce vibration in chamber with G-M cryocooler. So the pulse tube cryocooler has been carefully considered for cryopump application [1]. The pulse tube cryocooler, which has no moving parts at its cold section, is attractive in obtaining higher reliability, simpler construction, and lower vibration than any other small cryocooler [2, 3].

The pulse tube cryocooler was first described by W.E.Gifford and R.C. Longworth in 1963[4]. This type of the pulse tube cryocooler is now called as the basic pulse tube cryocooler. The performance of this pulse tube cryocooler has been greatly improved by introducing an orifice and a buffer volume added to the hot end of the

pulse tube. This type of the pulse tube cryocooler, which is called as the orifice pulse tube refrigerator, was modified by R.Radebaugh et al. in 1986[4-6].

In 1990, the double inlet pulse tube cryocooler, in which a bypass tube is connected between a pressure wave generator and the hot end of the pulse tube, was suggested by S.Zhu et al. [7]. The cooling capacity per unit mass flow rate through the regenerator is greatly increased in the double inlet pulse tube cryocooler. The cooling performance of the pulse tube cryocooler has been improved since 1990s and it can be a good candidate for substitution of Gifford-McMahon (GM) cryocooler or Stirling cryocooler.

So far pulse tube cryocooler has been believed that it has lower efficiency than a comparable Stirling, and G-M cryocooler. However, now the pulse tube process is understood as a Stirling process [8]. With this understanding, there are no physical reasons for having lower efficiency with a properly designed pulse tube cryocooler.

In this paper, research is focused on improving performance of 2 stage G-M type pulse tube cryocooler for cryopump application. The target cooling capacities of 2 stage pulse tube cryocooler are 5 W at 20 K and 35 W at 80 K for 1st and 2nd stage, respectively. So, we will describe design, fabrication and test processes of 2 stage pulse tube cryocooler with target cooling capacities. And, the effect of orifice valves and double inlet valves for the performance of the 2 stage pulse tube cryocooler will be investigated. Also cooling capacities of 2-stage pulse tube cryocooler will be measured and the pumping speed and the ultimate vacuum pressure of the cryopump will be discussed.

2. DESCRIPTION OF CRYOPUMP

In recent years, there is increasing demand for a clean, oil free vacuum with fast pump down cycle to high vacuum in most varied areas of vacuum technology. So cryopumps are nowadays used in different types of vapor deposition systems, sputtering in production of semiconductors, molecular beam epitaxy, plasma etching, electron beam welding furnaces and degassing furnaces due to their ultra clean vacuum, very high pumping speed for water vapor, hydrogen gas as well as for other gases [9].

A commercial cryopump uses 2 stage G-M cryocooler.

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

The 1st stage cold-end cools the 1st cryoarray and radiation shield and the 2nd stage cold-end cools the 2nd cryoarray.

Fig. 1 shows a typical configuration and principle of cryopump. Water vapor and carbon dioxide are trapped at the 1st cryoarray. Argon, nitrogen and 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.

3. PULSE TUBE CRYOCOOLER

3.1. Design and fabrication of the pulse tube cryocooler

Fig. 2 is the schematic diagram of 2 stage pulse tube cryocooler for commercialization. 2 stage pulse tube cryocooler consists of a helium compressor, regenerators, pulse tubes, heat exchangers, buffers, orifice valves, double inlet valves and rotary valve. All parts including rotary valve, buffers, orifice valves and double inlet valves are integrated in one module of the hot end region as shown in Fig. 3.

Design of 2 stage pulse tube cryocooler is conducted by FZKPTR(ForschungsZentrum Karlsruhe Pulse Tube Refrigerator) program [10] 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. The first stage regenerator is filled with phosphor bronze meshes. Thermal properties of the phosphor bronze are similar with those of stainless steel and phosphor bronze has a good workability for machining. The second stage regenerator is filled with lead shot balls with 250 μ m of nominal diameter. Lead is suited for the 2nd

stage regenerator because it has high heat capacity in the range of temperature from 50 K to 20 K. The brass meshes are also stacked at the cold end of pulse tube for flow straightening and heat exchange.

Rotary valve to generate pulsating pressure was directly connected to the inlet of the 1st stage regenerator to minimize pressure loss and compliance effect through connection part(Fig. 4). The materials of rotor and stator of rotary valve are vespel and SUS 316, respectively. And, rotary valve is driven by stepping motor (PK2913-02A, Oriental motor). The 2nd stage buffer is connected to the 1st stage by the connecting tube in the module of the hot end region. Orifice valves and double inlet valves are used as phase control devices. All phase control valves are newly designed and fabricated for integration in a single body as shown in Fig. 5.

Fig. 2. 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. Buffer, 7, 8. orifice valve, 9, 10. double inlet valve, 11. rotary valve, 12. He compressor [11, 12].

Fig. 3. Model description of 2 stage pulse tube cryocooler.

TABLE I
SPECIFICATION OF THE 2 STAGE PULSE TUBE CRYOCOOLER .

Items	1 st stage	2 nd stage
Regenerator	O.D. = 50.8 L = 175 t = 0.4	O.D. = 25.4 L = 150 t = 0.3
Regenerator material	#200 Phosphorous bronze mesh	Pb ball (Dia. = 250 ± 10 %)
Pulse tube	O.D. = 38.1 L = 175 t = 0.38	O.D. = 19.05 L = 300 t = 0.3
Reservoir	1 L	0.6 L

Fig. 4. Rotary valve, buffers and phase control valves.

Fig. 5. Configuration of phase control valves(valve body).

Fig. 6. Manufactured valves and test block.

Cooling characteristics of the pulse tube cryocooler vary with the phase difference between pressure and flow rate. Therefore, phase control valves must have a proper flow coefficient for each flow rate. Fig. 6 shows the manufactured valves and test block. Relations of pressure and flow rate with valve turns are measured with the degree of valve stem and diameter of valve orifice.

The flow coefficients of phase control valves which have a proper flow rate for 2 stage pulse tube cryocooler are experimentally measured as valve turns and the results are shown in Fig. 7.

(a) 1st orifice valve

(b) 1st double inlet valve

Fig. 7. Flow coefficients of the optimized phase control valves.

3.2. Performance results of the pulse tube cryocooler

The no load temperatures measured at the cold ends of 2 stage pulse tube cryocooler with operating frequency and valve turns are shown in Fig. 8. In this experiment, the 2nd stage orifice and double inlet valve were 5 turns and 2 turns, respectively.

The lowest temperature of the 1st stage cold end was measured when the 1st stage orifice and double inlet valve were 2.5 turns and 1 turn, respectively. The lowest temperature of the 1st stage cold end was 42.0 K at the operating frequency of 2.2 Hz. And, the lowest temperature of the 2nd stage cold end was measured when the 1st stage orifice and double inlet valve were 3 turns and 1 turn, respectively. The lowest temperature of the 2nd stage cold end was 8.3 K at the operating frequency of 2.2 Hz. In Fig. 8, the lowest temperatures of the 1st and the 2nd stage cold end at the operating frequency 2.2 Hz were similar with those at the operating frequency 2 Hz. The friction load of the rotary valve increases and life time decreases as the rotating frequency increases. Therefore, operating frequency of the 2 stage pulse tube cryocooler was selected with 2 Hz for cryopump. The results of the cooling

Fig. 8. The no load temperatures measured at the cold ends of 2 stage pulse tube cryocooler with operating frequency and valve turns.

Fig. 9. Cooling capacities with the 1st and the 2nd cold end temperature.

capacities are shown in Fig. 9. Cooling capacity tests were performed using the electric heaters of 50 W which are attached at the cold ends of each pulse tubes.

In this case, the 1st stage orifice and double inlet valve were 3 turns and 1 turn, and the 2nd stage orifice and double inlet valve were 5 turns and 2 turns, respectively. The cooling capacities were 40 W at 82.9 K on the first stage and 10 W at 20.5 K on the second stage.

In general, cooling capacities for cryopump depend on their specification and design. The target cooling capacities were 5 W at 20 K and 35 W at 80 K for the 1st and the 2nd stage, respectively. These values were good cooling capacities for vacuum level in medium size cryopump having 3,500 L/s of the pumping speed for Nitrogen.

4. TEST RESULTS OF THE CRYOPUMP

4.1. Fabrication of the cryopump

In order to validate the cryopump with 2 stage pulse tube cryocooler, tests were performed for pumping speed and ultimate pressure measurement of cryopump using nitrogen (type-II gas).

Cryopump consists of 2 stage pulse tube cryocooler, 1st cryoarray, 2nd cryoarray, radiation shield and vacuum chamber as shown in Fig. 10.

Fig. 11 shows test apparatus of 16.5 inch cryopump. Vacuum chamber of Ø 16.5 inch was used in baked condition.

This test vacuum chamber had three ports for instrumentation. One was fine leak valve port for in-leaking test gas with CF flange, the second one was for high vacuum gauge such as ion gauge with CF25 flange and the third one was optional port for the residual feedthrough with CF flange. With this configuration, tests were performed to measure characteristics of cryopump like base pressure, cool-down time, pumping speed, ultimate vacuum pressure for nitrogen.

Fig. 12 shows test apparatus for measuring pumping speed of the cryopump. Turbo molecular pump(TMP) was used for roughing of the vacuum chamber.

Fig. 10. Configuration of the cryopump.

Fig. 11. 16.5 inch cryopump and test apparatus.

4.2. Pumping speed and ultimate pressure of the cryopump

The tests for pumping speed measurement of nitrogen were carried out by constant pressure flow meter method. The standard volume flow rate of nitrogen in-leaked into vacuum chamber was measured by mass flow controller of Sierra. Pressure in test chamber was measured with stabilion gauge of Granville-Phillips.

Fig. 13 shows cold ends temperatures, input power and pumping speed of the cryopump. Maximum pumping speed of the cryopump for Nitrogen was 4,300 L/s. In this case, the 1st and the 2nd cold end temperatures were 47 K and 10 K, respectively, and compressor input power was about 6 kW.

Fig 14 shows the ultimate vacuum pressure of the cryopump with 2 stage pulse tube cryocooler. The ultimate vacuum pressure of the cryopump with 2 stage pulse tube cryocooler was below 7.5×10^{-10} mbar.

Fig. 12. Test apparatus for measuring pumping speed of the cryopump.

Fig. 13. Performance results of the cryopump.

Fig. 14. Vacuum pressure of the cryopump.

5. SUMMARY

Pulse tube cryocooler technology has made rapid advancements in recent years, and two remarkable advantages of pulse tube cryocooler have emerged. These include the elimination of moving parts and potential wear at the cold end, and the significantly reduced vibration output level of the cold finger due to the absence of a moving displacer. These advantages have provided the pulse tube cryocoolers with the potential to replace G-M cryocoolers in the cryopump.

So, we have undertaken experimental researches for improving performance of 2 stage pulse tube cryocooler for cryopump. Following conclusions are drawn from the experimental results.

- (1) 2 stage pulse tube cryocooler including rotary valve, buffers, orifice valves and double inlet valves in the module of the hot end region was designed and fabricated for cryopump.
- (2) When the operating frequency of 2 stage pulse tube cryocooler was 2.2 Hz, the no load temperatures reached 42.0 K at the 1st stage cold end and 8.3 K at the 2nd stage cold end, respectively.
- (3) 2 stage pulse tube cryocooler for cryopump was operated with 2 Hz of operating frequency and the cooling capacities were 40 W at 82.9 K on the first stage and 10 W at 20.5 K on the second stage.
- (4) Maximum pumping speed of the cryopump for Nitrogen was 4,300 L/s and the ultimate vacuum pressure was below 7.5×10^{-10} mbar.

These results of 2 stage pulse tube cryocooler are good cooling capacities for vacuum level in medium size cryopump having 3,500 L/s of the pumping speed for Nitrogen.

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