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Experimental Study on a GM-type Two-Stage Pulse Tube Refrigerator for Cryopump Applications

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Abstract-- **A single-stage and two-stage pulse tube refrigerators have been designed for cryopump application. The different diameters of pulse tube and regenerator have been investigated at single-stage pulse tube refrigerator(PTR). Experiments have been performed on single-stage PTR to reach minimum temperature with optimum valve opening at a few frequencies. And the two-stage pulse tube refrigerators have been assembled with tested single-stage pulse tube and tested. When orifice turn is opened to 9 and double inlet is opened to 3 at a single-stage, the lowest temperature of 33.7 K is achieved. The cooling capacity at single-stage is 38 W at temperature of 80 K. A two-stage pulse tube refrigerator has 16.3K at the second stage and 59.7K at the first stage. The cooling capacity achieved is 16.5 W at 80 K, the first stage and 0.6 W at 20 K, the second stage. Some details on the design of pulse tube refrigerator and the experimental apparatus are given.**

1. INTRODUCTION

In 1963, Gifford and Longsworth devised a method known as pulse tube refrigeration which eliminated the cold end displacer from the Stirling cryocooler[1]. In this method gas is pulsed in and out of a tube closed at the other end. The gas passes through a regenerator before entering the pulse tube. Refrigeration occurs at the open end and heat is rejected at the closed end of pulse tube. A major improvement in performance was achieved by Mikulin *et al.*[2] who provided the closed end of the pulse tube with an orifice connected to a reservoir. The resulting geometry has become known as orifice pulse tube refrigerator, while the original geometry described by Gifford and Longsworth is called the basic pulse tube refrigerator. Another improvement in performance was reported by Zhu *et al.*[3] who added a tube that connects the regenerator and the pulse tube. They refer to their geometry as the double inlet pulse tube refrigerator.

In the early days, PTRs were considered most attractive device because of their simple design, low vibration, and projected high reliability. And it was believed that lower efficiency than that of a comparable Stirling, and Gifford-McMahon(GM) cooler had to be accepted.

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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 this has been verified for compact single-stage Stirling-type refrigerators[4] and also for GM-type pulse tube systems[5]. With multi-stage GM-type PTRs even temperatures in the range of 2 K are being achieved.[6,7]

In some semiconductor equipments, a vibration is very critical parameter in design. And an isolator has been used to reduce vibration in chamber with GM cooler. So the PTRs have been carefully considered for cryopump application because it has no moving parts at low temperature.

In this paper, research is focused on a two-stage GM-type PTR with 4.5 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 two-stage PTR. Also cooling capacities of single- stage and two-stage PTR at the first stage, 80 K and at the second stage, 20 K will be measured. This study has been carried out for two years and a cryopump with two-stage PTR will be developed within two years for any applications.

2. EXPERIMENTAL APPARATUS

Single-stage and two-stage pulse tube refrigerators were fabricated and tested as shown in Fig. 1. The experimental apparatus consists of a helium compressor, regenerators, pulse tubes, heat exchangers, reservoirs, orifice valves, double inlet valves and solenoid valves. The pulse tubes and regenerators are flanged to dismantle and easily switched for other test. Pressures are measured at the warm end of the first stage regenerator, the warm end of the first stage pulse tube and inlet of the reservoir. Temperature sensors are attached on the both cooling stations of the regenerators and pulse tubes. And 5 temperature sensors are also attached on the outer surface of pulse tube with equally spaced. The resistant heat wires are wounded on the cooling stations to measure cooling capacity.

TABLE I
GEOMETRY OF PULSE TUBES AND REGENERATORS.

		Pulse tube (mm)	Regenerator (mm)	Matrix
First stage	Case I	Φ 31 x 150 L	Φ 42 x 175 L	No. 150 phosphor bronze mesh
	Case II	Φ 38 x 150 L	Φ 50 x 175 L	No. 200 phosphor bronze mesh
Second stage		Φ 19 x 300 L	Φ 25 x 150 L	Φ 0.3 - 0.4 mm lead shot ball

The oscillating pressure is generated by a valved compressor which is commonly used in GM refrigerators. The input power of compressor(HC 70®, Genesis) is about 4.5 kW. The on-off timing is controlled by a rotary timer and solenoids. Operational frequency is 1-3 Hz. Two reservoirs are connected with each pulse tube and volume of reservoir used here is about 5000 cm^3. During the experiment, a vacuum chamber was connected to the high vacuum pump under pressure of 10^{-5} Torr.

The orifice and double inlet valves are an adjustable needle valve which has 0.03 of flow coefficient and full opening is 9 turns. A description of the PTR is given in Table 1. The diameter of regenerator and pulse tube at the first stage are considered affecting minimum temperature in this study. And 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 coolers. The brass meshes are also stacked at the cold end of pulse tube for flow straightening and heat exchange.

Air cooled heat exchangers that brass meshes are stacked, are located on the warm ends of both pulse tubes.

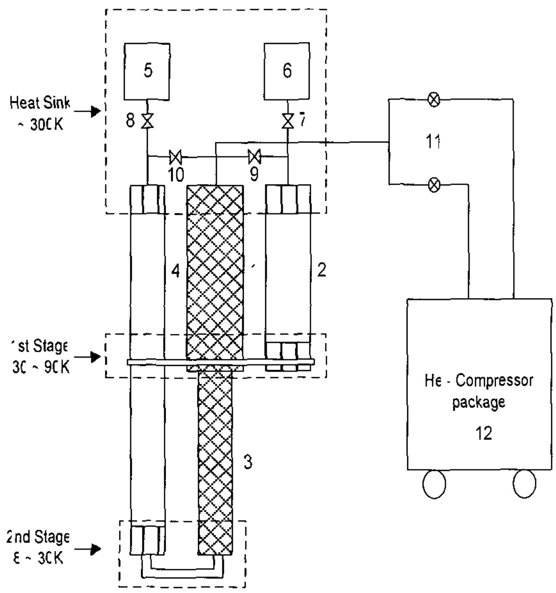

Fig. 1. Schematic diagram of two-stage pulse tube refrigerator: 1. 1st stage regenerator, 2. 1st stage pulse tube, 3. 2nd stage regenerator, 4. 2nd stage pulse tube, 5,6. reservoir 7,8. orifice valve, 9,10. double inlet valve, 11. solenoid valve, 12. He compressor.

3. EXPERIMENTAL RESULTS

Pressure waves shown in Fig. 2 were measured at the warm side of regenerator when the system was at the steady state. With temperatures at the cold end of each stage dropping, pressure waves obviously change and pressure ratio decreases and curves become smooth.

The pressure of reservoir on the graph is nearly steady and it means that buffer size is enough for oscillating flow through the pulse tube. In this experiment, valve opening is main controlling parameter to reach minimum temperature at the PTR. The refrigeration performances of PTR have been tested continuously through valve opening. The first step was aimed at getting no load minimum temperature at a single- stage. The experiments were carried out to get optimum valve opening.

The effect of the double inlet valve opening to orifice valve opening is measured as shown in Fig. 3 and 4. First in the orifice pulse tube refrigerator with closed double inlet valve, the lowest temperature is 105.5 K for case I as shown in Fig. 3 and 45.6 K for case II as shown in Fig. 4. As double inlet opens further, temperature decreases sharply.

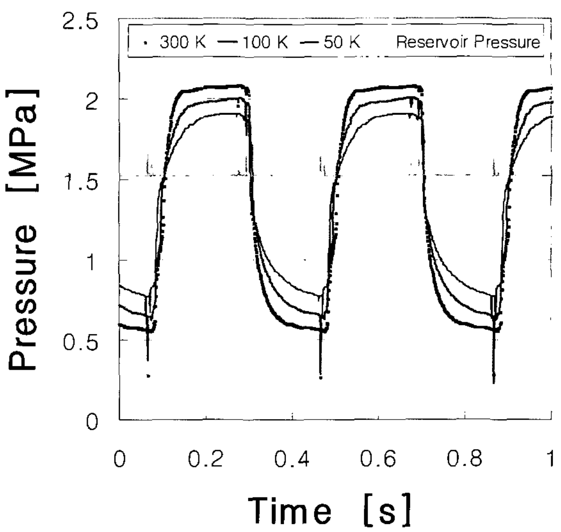

Fig. 2. Pressure wave variations with cold end temperature at 2.5 Hz in case II.

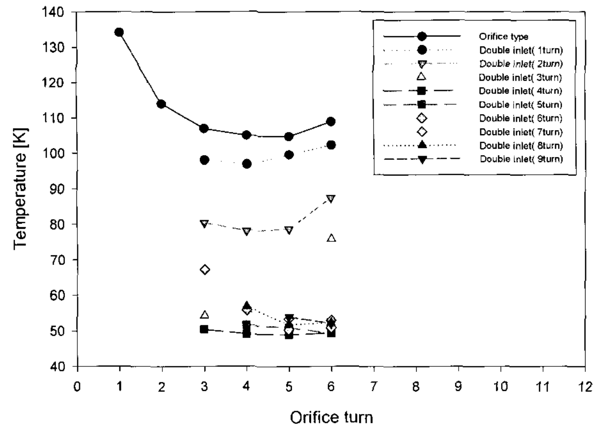

Fig. 3. Temperature variation with orifice and double inlet valve opening at the single-stage, 2.5 Hz, in case I.

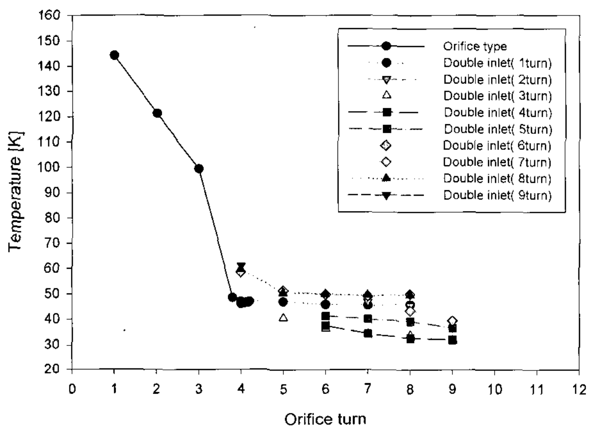

Fig. 4. Temperature variation with orifice and double inlet valve opening at the single-stage, 2.5 Hz, in case II.

However temperature increases on the contrary at double inlet 5 turns(one turn means one circle). It means that optimum valve opening exists at each pulse tube. Fig. 3 shows temperature profile with double inlet opening in single-stage pulse tube refrigerator. When orifice is opened to 5 turns and double inlet is opened to 4 turns, temperature is 48.9 K.

As double inlet opens further, temperature decreases slightly and when orifice is opened to 9 turns and double inlet is opened to 3 turns, the lowest temperature of 33.7 K is achieved in Fig. 4. This can be explained that cooling capacity per unit mass flowing through the regenerator is increased by the double inlet valve. Expansion volume of gas piston by pulse tube diameter and heat exchange area by mesh size in the case II is larger than in the case I and it affects minimum temperature.

The cooling capacity of single-stage pulse tube refrigerator with the lowest temperature of 33.7 K is about 38 W at 80 K shown in Fig. 5. From the above results, pulse tube diameter and length, regenerator diameter and length should be redesigned to get a large cooling capacity. And orifice and double inlet valve opening should be optimized at a given single-stage pulse tube refrigerator to reach the minimum temperature.

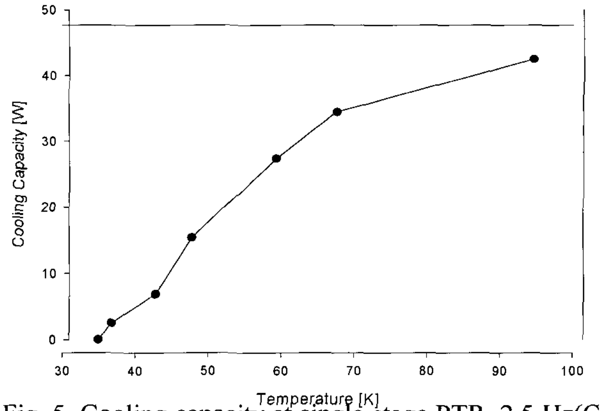

Fig. 5. Cooling capacity at single-stage PTR, 2.5 Hz(Case II).

The two-stage pulse tube refrigerators have been assembled with previous tested single-stage pulse tube and second stage pulse tube and regenerator. Fig. 6 and 7 show temperature variation with orifice and double inlet valve opening at the second stage. As the orifice opens, temperatures decrease but increase at some valve opening in general. When orifice is opened to 4 turns and double inlet is opened to 3 at the first stage, minimum temperature reaches 20.2 K at orifice 4 turns and double inlet 3 turns as shown in Fig. 6.

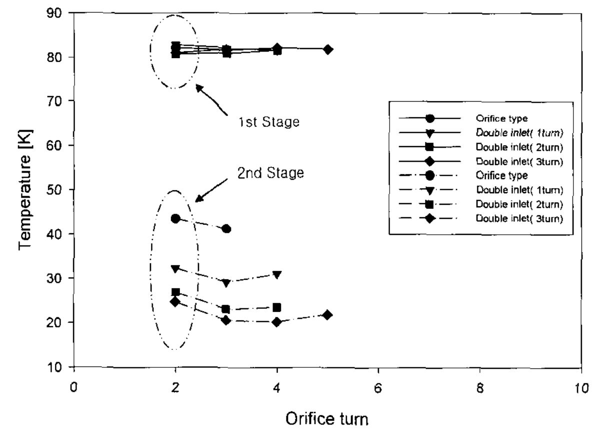

Fig. 6. Temperature variation with orifice and double inlet valve opening at two-stage, 2.5 Hz, in case I.

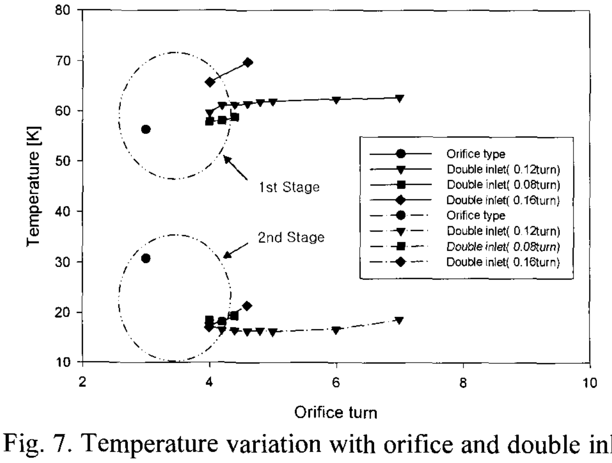

Fig. 7. Temperature variation with orifice and double inlet valve opening at two-stage, 2.5 Hz in case II.

When double inlet valve opens one turn, temperature increases sharply in test. This means that a small DC flow has a large effect on performance. When orifice is opened to 9 turns and double inlet is opened to 3 at the first stage, minimum temperature reaches 16.3 K at orifice 4 turns and double inlet 0.12 turn in Fig. 7.

Fig. 8 shows cooling capacity at each lowest temperature, 2.5 Hz in case II. The cooling capacity of two-stage pulse tube refrigerator is 16.5 W at 80 K for the first stage and 0.6 W at 20 K for the second stage. In general, cooling capacities for cryopumps depend on their specification and design. The target cooling capacities were 5 W at 20 K, the second stage and 35 W at 80 K, the first stage to reach a good cool-down time and vacuum in medium size ICP 200 cryopump.

This small capacity is not enough for cryopump application. To get the larger capacity, diameter, length and valve opening of pulse tube and regenerator at the first stage and the second stage should be optimized. A cool down behavior is shown in Fig. 9. This indicates process of reaching the lowest temperature with valve opening.

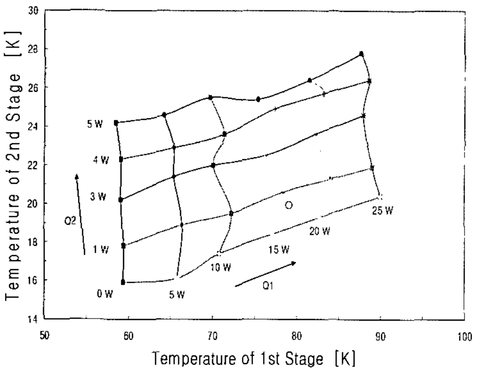

Fig. 8. Cooling capacities and temperatures achieved with HC 70® compressor at 2.5 Hz in case II.

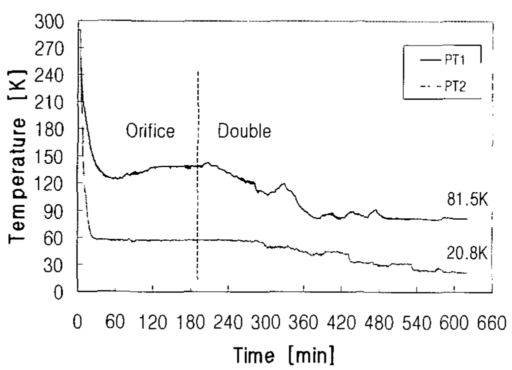

Fig. 9. Cool down curve at two-stage pulse tube refrigerator in case I.

Also temperature of the double inlet pulse tube refrigerator is lower than one of the orifice pulse tube refrigerator. The lowest temperature reached 20.8 K at the second stage.

4. SUMMARY

The cooling performance with valve opening of the orifice valve and double inlet valve has been experimentally investigated for single-stage and two-stage PTRs. The optimization of pressure ratio, length of pulse tube and regenerator has not been carried out yet. However, the lowest temperature of a two-stage PTR operating at room temperature reaches 16.3 K at orifice 4 turns and double inlet 0.12 turn.

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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