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An Experimental Investigation of the G-M type Pulse Tube Refrigerator

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***Abstract*-- The experimental results of the G-M (Gifford-McMahon) type pulse tube refrigerators are presented in this paper. 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 refrigerators. The objectives of this study are to develop the design technology of the G-M type pulse tube refrigerator and acquire its application methods for replacing G-M cryocooler. As a preliminary test, the refrigeration performances of the basic, orifice, and double inlet pulse tube refrigerators were investigated. The lowest temperature obtained in the one-stage pulse tube refrigerator was 34.4K and the refrigeration capacity at the optimum operation condition was 23W at 80K. And the lowest temperature of the second stage cold head in the two-stage pulse tube refrigerators was 18.3K and the refrigeration capacities at optimum condition were 0.45W at 20K and 20W at 80K, respectively. Finally, the lowest temperature obtained in the three-stage pulse tube refrigerator was 29.8K and the refrigeration capacity at the optimum operation condition was 1.3W for 40K and 5W for 70K.**

1. INTRODUCTION

W.E.Gifford and R.C.Longsworth [1] in1964 first described the pulse tube refrigerator. This type of the pulse tube refrigerator is now called by the basic pulse tube refrigerator. But practical development did not proceed until E.L.Mikulin et al. [2] discovered the "Low-Temperature expansion pulse tube refrigerator" in 1984. This performance of the pulse tube refrigerator 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 refrigerator, called by the orifice pulse tube refrigerator, was modified by R.Radebaugh et al. [3] in 1986, and then reached the lowest temperature of 60K. In 1990, the double inlet type of the pulse tube refrigerator, in which bypass the connects between a pressure wave generator and the hot end of the pulse tube, was suggested by S.Zhu et al. [4]. Performance of the double inlet pulse tube refrigerator, by increasing the refrigeration power per unit mass flow rate through the regenerator, was greatly improved [5].

A study of the multiple-stage pulse tube refrigerator was performed to achieve much lower temperature. R.C.Lonsworth reported the lowest temperatures of 79K and 31K, respectively by designing the basic type two-stage and three-stage pulse tube refrigerator. Thereafter, Y.Zhou et al. [6] and E.Tward et al. [7] achieved the lowest temperatures of 31K and 26K, respectively by orifice type two-stage pulse tube refrigerators. Matsubara et al. [8] investigated the performance of the pulse tube refrigerator below 15K by using a two-stage Gifford-McMahon refrigerator to precool the hot end of the final stage regenerator. Recently, J.L.Gao et al. [9] succeeded in achieving the lowest temperature of 3.6K by a three-stage pulse tube refrigerator.

In this paper, firstly we report on the performance test data from the single-stage basic, orifice, and double inlet pulse tube refrigerator. And then, according to the method of the multiple staging presented by Y.I.Matsubara, two-stage and three-stage pulse tube refrigerator were fabricated. Experimental results of the two-stage and three-stage pulse tube refrigerator are described.

2. EXPERIMENT DESCRIPTION

2.1. Single-stage pulse tube refrigerator

Experimental apparatus of the single-stage pulse tube refrigerator is shown in Fig. 1. The refrigerator consists of a compressor, heat exchanger, regenerator, pulse tube, orifice (adjustable needle valve), double inlet valve, reservoir and vacuum chamber. The pressure oscillation is generated by using a commercial helium compressor (CTI Cryogenics 8300) for Gifford-McMahon refrigerator and solenoid valves with rotary timer for adjusting operating cycle frequency. The helium compressor has an electrical input power of 2.2kW.

The regenerator and pulse tube are made of thin-walled stainless steel tubes with 35mm i.d. × 100 mm length and 21 mm × 203 mm length, respectively. Volume ratio of the regenerator to the pulse tube is 1.33. The regenerator matrix consists of a stack of 1,000 bronze screens of 250 meshes. The heat exchangers/flow straightners at both ends of the pulse tube are packed with 50 stainless steel screens of 200 meshes. The hot end heat exchangers of the regenerator and the pulse tube are only cooled with circulating cooling water. The rate of heat extraction from the hot end of the pulse tube is derived from a mass flow rate and a temperature increase of the circulating water. The volume of the reservoir is 1,000 cm^3. Orifice and double inlet valves are used as the adjustable needle valves (C_V=0.03).

Strain gauge type pressure transducers (Kyowa PVL-50 KD) are used to monitor the pressure oscillations at the hot ends of the regenerator and pulse tube and in the reservoir. Cold head temperature of the pulse tube is measured by a silicon-diode thermometer (Lakeshore DT-470). A resistance of a manganese wire is provided at the cold end of the pulse tube for the refrigeration capacity measurement. After attaching every sensor, the cold end of the pulse tube is wrapped with multi-layer insulation (MLI) for radiation shield, and apparatus of the pulse tube refrigerator except for the component of the room temperature region is inserted in the vacuum chamber. During the experiment, a vacuum chamber is connected to the high vacuum pump under a pressure of 10^{-5}Torr. High vacuum pump system consists of the rotary roughing pump, diffusion pump and vacuum gauges.

After the regenerator of the pulse tube refrigerator is purged by evacuating vaporization and sending clean high-pressure helium gas, the pulse tube refrigerator is connected to the compressor. Then, system is charged up to $15kg_f/cm^2$. In the experiment, the test apparatus acts as a basic pulse tube refrigerator if orifice and double inlet valve are close, and orifice pulse tube refrigerator if orifice is open and double inlet valve closed, finally double inlet pulse tube refrigerator if orifice and double inlet valve are open.

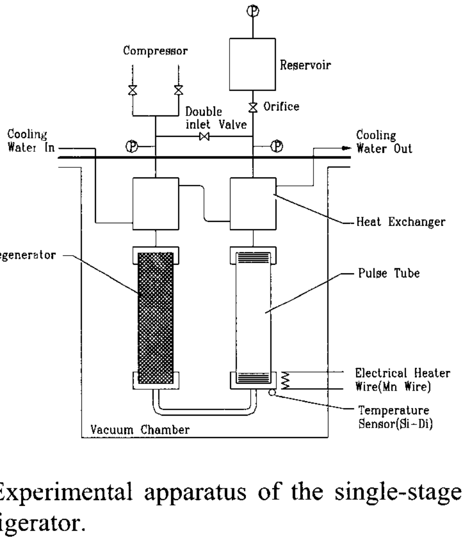

Fig. 1. Experimental apparatus of the single-stage pulse tube refrigerator.

2.2. Two-stage pulse tube refrigerator

Fig. 2 shows the experimental apparatus of the two-stage pulse tube refrigerator. In general two-stage pulse tube refrigerator, the hot end of the second pulse tube is cooled by the first refrigeration stage. In this paper, however, the hot end of the first and second pulse tubes are connected to the air cooling heat exchangers in the room temperature region. This type of the multi-stage pulse tube refrigerator has been suggested by Y.I.Matsubara and has shown good results.

Regenerator and pulse tubes are made of the thin-walled stainless steel tube. The first and second regenerators are 35mm i.d. × 100mm length and 35mm i.d. × 80mm length with a stack of 1,000 bronze screens of 250 mesh and lead spheres (φ0.2mm - 0.3mm), respectively. The first and second pulse tubes are 21mm i.d. × 203mm length and 17.8mm i.d. × 200mm length, respectively. The volumes of the reservoirs are 1,000cm^3. Each orifice and double inlet valve used the adjustable needle valves (C_V=0.03). Pressure transducers, thermometers and heater wires used for the single-stage pulse tube refrigerator are used for the two-stage pulse tube refrigerator. Pressure is measured at the hot ends of the regenerator and pulse tubes and in the reservoirs. Temperature is monitored at the cold ends of the first and second pulse tubes. Heater wires are provided at the cold ends of the first and second pulse tubes. In addition, each stage has double inlet lines provided with double inlet valves. Charged pressure of the two-stage pulse tube refrigerator system is $15kg_f/cm^2$. Experimental process is progressed by same manner of the single-stage pulse tube refrigerator.

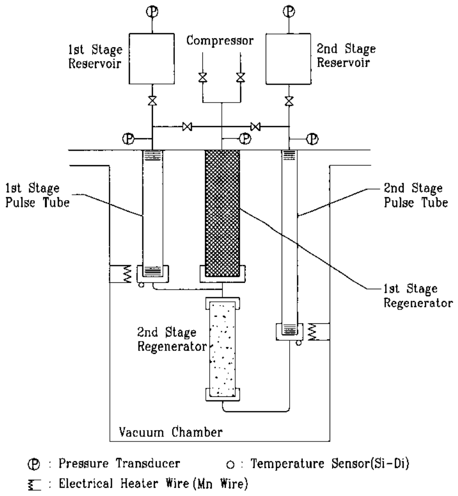

Fig. 2. Experimental apparatus of the two-stage pulse tube refrigerator.

2.3. Three-stage pulse tube refrigerator

Experimental apparatus of the three-stage pulse tube refrigerator is shown in Fig 3. The refrigerator consists of a compressor, regenerators, pulse tubes, regenerative tube in the high temperature region of the 3rd stage pulse tube, orifices (adjustable needle valve), double inlet valves, reservoirs and vacuum chamber. The pressure oscillation is generated by using a commercial helium compressor for Gifford-McMahon refrigerator and solenoid valves with rotary timer for adjusting the frequency of the operating cycle. The helium compressor has an electrical input power of 2.2kW. The regenerative tube [8, 9] is inserted between the hot end of the pulse tube and the double inlet phase shifter at room temperature. Without the regenerative tube, the temperature difference (about 296 K

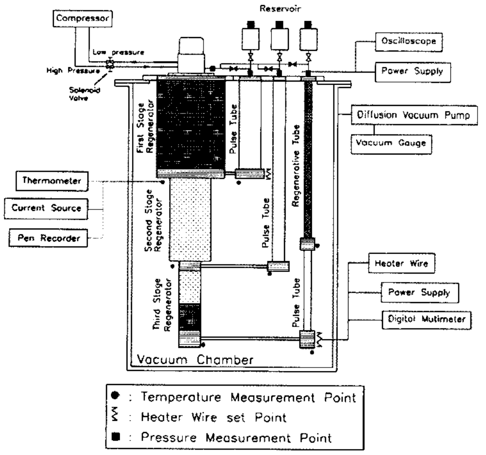

Fig. 3. Experimental apparatus of the three-stage pulse tube refrigerator.

from 300 K to 4.2 K) between the hot end and cold end of the 3rd pulse tube is very large. To reduce the peak temperature along the pulse tube, one of reasonable methods is to install a sort of regenerator between the warm end of the pulse tube and the second inlet tube at room temperature.

Table 1 shows dimensions and materials of pulse tubes, regenerative tube and reservoirs in the three-stage pulse tube refrigerator. The flow straightners at both ends of the pulse tubes are packed with 50 stainless steel screens of 200 meshes. The adjustable needle valves (C_v = 0.03 at full-open, 9 turn-open) are used as the orifice and the double inlet valve

TABLE 1.
Dimensions and materials of the three-stage pulse tube refrigerator.

Items	Materials	Sizes (mm)
1st stage regenerator	Stainless steel tube filled with #200 bronze mesh	ϕ 50 × 0.5 × 160, V_{R1} = 314cm^3, Porosity = 0.62
2nd stage regenerator	Stainless steel tube filled with lead shot (ϕ 0.2- 0.3mm, 617g)	ϕ 30 × 0.38 × 115, V_{R2} = 81.3cm^3 Porosity = 0.36
3rd stage regenerator	Stainless steel tube filled with Er_3Ni shot (ϕ 0.2- 0.4mm, 202g)	ϕ 21 × 0.38 × 135, V_{R3} = 46.8cm^3 Porosity = 0.34
Regenerative tube	Stainless steel tube filled with lead shot (ϕ 0.2- 0.3mm, 103g)	ϕ 9 × 0.25 × 235, V = 15cm^3 Porosity = 0.36
1st stage pulse tube	Stainless steel tube	ϕ 24.5 × 0.38 × 180, V_{P1} = 84.9cm^3
2nd stage pulse tube	Stainless steel tube	ϕ 21 × 0.38 × 150, V_{P2} = 52cm^3
3rd stage pulse tube	Stainless steel tube	ϕ 9 × 0.25 × 140, V_{P3} = 38.9cm^3
Reservoirs	Stainless steel tube	V = 1,000cm^3

Strain gauge type pressure transducers are used to monitor the pressure oscillations at the hot ends of the regenerator and the pulse tubes and the reservoirs. The cold head temperature of the pulse tube is measured by using a silicon-diode thermometer. A manganese resistance heater is provided at the cold end of the pulse tube to measure the refrigeration capacity. After attaching all sensors, the cold end of the pulse tube is wrapped by multi-layer insulation (MLI) for radiation shield, and the apparatus of the pulse tube refrigerator except the component of the room temperature region is connected to the vacuum flange. During the experiment, a vacuum chamber is connected to the high vacuum pump under a pressure of 10^{-5} Torr. The high vacuum pump system consists of a rotary roughing pump, a diffusion pump and vacuum gauges. Charged pressure of the three-stage pulse tube refrigerator system is 15kg$_f$/cm^2.

3. EXPERIMENT RESULTS

3.1. Single-stage pulse tube refrigerator

As a preliminary test, the refrigeration performance of the single-stage pulse tube refrigerator was investigated as the basic, orifice and double inlet type. Fig. 4 shows the cool-down characteristics of the basic, orifice and double inlet pulse tube refrigerators at operating frequency 1.5 Hz. Pressure ratios decrease gradually 2.6 (21 kg$_f$/cm^2 / 8 kg$_f$/cm^2) to 1.9 (19 kg$_f$/cm^2 / 10 kg$_f$/cm^2) as the temperature of the cold end decreases. The cooling rate of the orifice and double inlet pulse tube refrigerators is faster than that of the basic pulse tube refrigerator. The lowest no load temperature of the basic, orifice and double inlet pulse tube refrigerators at the operating frequency 1.5Hz was 174.1K, 74.6K, and 47.5K, respectively.

Fig. 5 shows the variations of the cold head temperature with operating frequency for the basic, orifice and double inlet pulse tube refrigerator. These measured results correspond to the optimized needle valve adjustments leading to the lowest cold end temperature. The lowest temperature 34.4K has been obtained in the double inlet pulse tube refrigerator at the operating frequency of 2.5Hz. The lowest temperature of the orifice pulse tube refrigerator was 59.14K at the operating frequency of 2.5Hz. As the measured results are investigated, optimal operating frequency for the lowest temperature at the cold

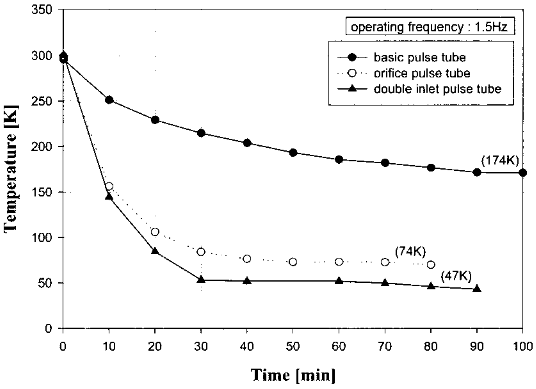

Fig. 4. Cool-down characteristics of the single-stage pulse tube refrigerators.

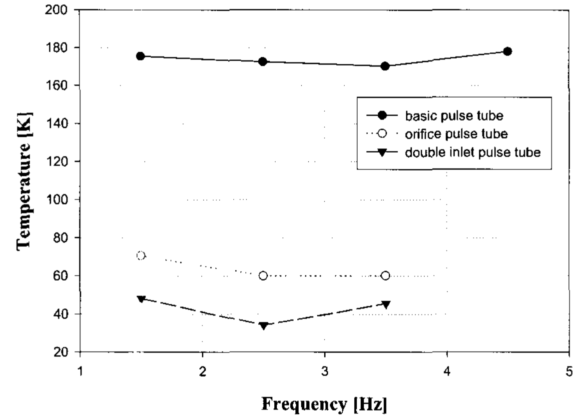

Fig. 5. The variations of the cold head temperature with operating frequency for the single-stage pulse tube refrigerator.

end of the pulse tube is high in order of the basic, orifice and double inlet pulse tube refrigerator.

Fig. 6 shows the behavior of the refrigeration capacity with operating frequency for the orifice and double inlet pulse tube refrigerator. Refrigeration capacity increases with the operating frequency in the orifice pulse tube refrigerator and is maximal at the operating frequency of 2.5Hz in the double inlet pulse tube refrigerator.

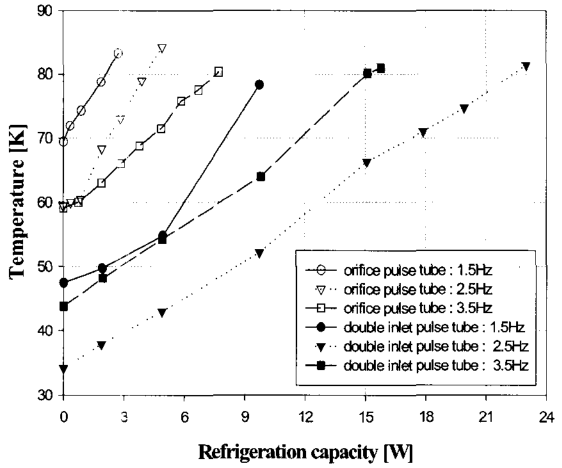

Fig. 6. The refrigeration capacity with operating frequency for the orifice and double inlet pulse tube refrigerator.

Maximum refrigeration capacities of the orifice and double inlet pulse tube refrigerator are 8W and 23W at the cold end temperature of 80K, respectively.

3.2. Two-stage pulse tube refrigerator

Fig. 7 shows the variations of no load temperature at the cold end of the second stage as a function of the first and second orifice valve opening with the first and second double inlet valve closed. In the two-stage orifice pulse tube refrigerator, the optimal condition leading to the lowest temperature of the second stage cold end is not strongly concerned with the opening rate of the first stage orifice valve. The lowest temperature of the second stage cold end is measured when the second stage orifice valve is 2 turns-open. In this case, the lowest temperature was 34.8K.

In Fig. 8 the relationship between the refrigeration capacities of the second stage cold end and the temperature of the first and second stage cold ends are displayed for the two conditions. Firstly (case A), the first, second orifice and second double inlet valves are 3 turns, 3 turns and 4 turns-open, respectively. Secondly (case B), the first, second orifice and second double inlet valves are 5 turns, 3 turns and 4 turns-open, respectively. The lowest temperature and refrigeration capacity of the second stage cold end in the case A are 18.85K and 0.45W, 20W at 20K, 80K, respectively. And the lowest temperature and refrigeration capacity of the second stage cold end in the case B are 18.27K and 18W at 80K, respectively. Temperatures of the first stage cold ends are decreased by increasing the temperature of the second stage cold end with the refrigeration load.

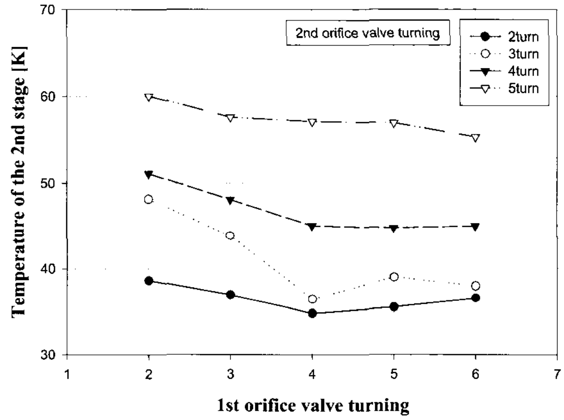

Fig. 7. The variations of no load temperature with orifice valve opening in the two-stage pulse tube refrigerator.

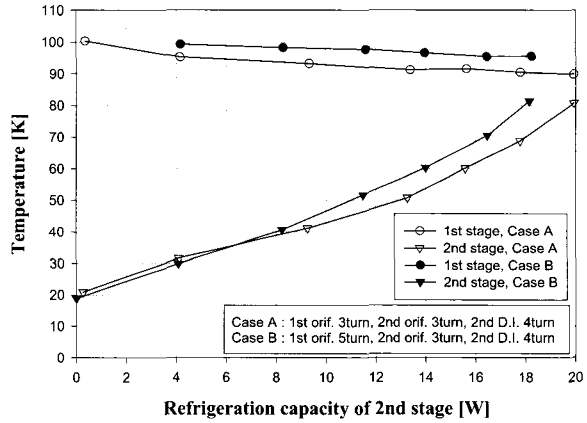

Fig. 8. The relationship between the refrigeration capacity of the second stage cold end and the temperature of the first and second stage cold ends.

3.3. Three-stage pulse tube refrigerator

Fig 9 shows the cool-down characteristics of the three-stage pulse tube refrigerator at the cycle frequency of 2Hz with the third stage double inlet valve of 2 turns-open (the first, the second and the third stage orifice valve openings were 3 turns-open, 3 turns-open and 2 turns-open, respectively). The lowest temperature of the third stage cold end was 43.72K. Fig 10 shows no load temperature of the each stage as a function of the third stage double inlet valve open (the first, the second and the third stage orifice valve openings were 3 turns-open, 3 turns-open and 2 turns-open, respectively).

Dead volume in the pulse tube refrigerator has a large effect on the cool-down characteristics and refrigeration capacity. However, as can be seen in Fig 11, when the dead volume in the hot end of the three-stage pulse tube refrigerator was reduced from 1.0 cc to 0.2 cc, the time required to cool down was shorter than that of the result in Fig 9 and the lowest temperature of the third stage cold end decreased to 33.7K.

Fig. 12 shows the behavior of the refrigeration capacity in the pulse tube of the each stage. The third stage double inlet valve was 1.2 turn-open and the first, the second and the third stage orifice valves were 3 turns-open, 2 turns-open and 2 turns-open, respectively. The lowest no load temperature and the refrigeration capacity of the third stage cold end are 29.8K and 1.3W and 5W at 40K and 70K, respectively.

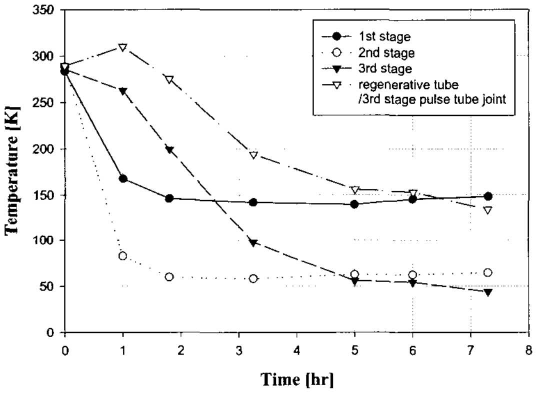

Fig 9. The cooldown characteristics of the three-stage pulse tube refrigerator.

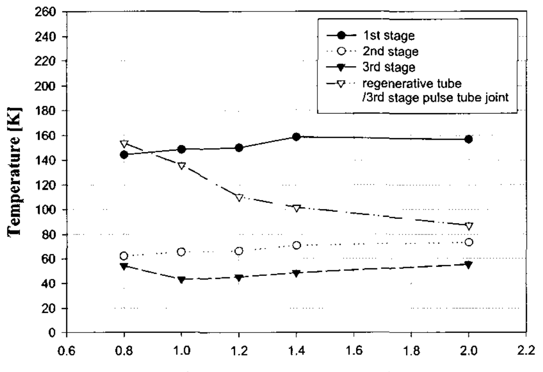

Fig 10. No load temperatures of each stage as a function of the third stage double inlet valve opening.

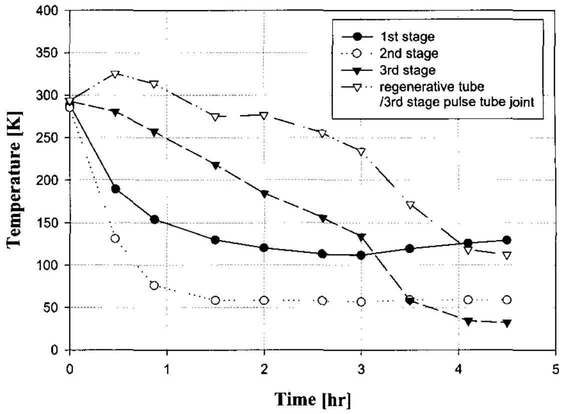

Fig 11. The cool-down characteristics of the revised three-stage pulse tube refrigerator.

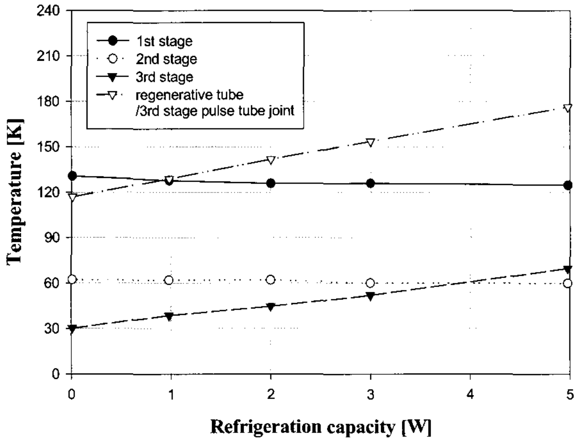

Fig 12. Load characteristics of the three-stage pulse tube refrigerator.

4. CONCLUSION

A single-stage, two-stage and three-stage pulse tube refrigerator were designed, fabricated and tested. The following conclusions are drawn from the investigation results.

(1) In the single-stage pulse tube refrigerator, cooldown characteristics at the operating frequency of 1.5 Hz and the variations of the cold head temperature with operating frequency were evaluated for the basic, orifice and double inlet pulse tube refrigerator. The cooling rates of the orifice and double inlet pulse tube refrigerators are faster than that of the basic pulse tube refrigerator. The lowest temperature of the orifice and double inlet pulse tube refrigerator reached 59.14K and 34.4K at the operating frequency of 2.5Hz, respectively.

(2) In the two-stage orifice pulse tube refrigerator with the first and second double inlet valve closed, the optimal condition is not concerned with the opening rate of the first stage orifice valve. The lowest temperature achieved was 34.8K at the operating frequency of 2.5Hz when the first and second stage orifice valves are 4 turns-open and 2 turns-open, respectively.

(3) In the two-stage pulse tube refrigerator with the second stage double inlet valve opened 4 turns, the lowest no load temperature of the second stage cold end was 18.27K, refrigeration capacity of the second stage cold end were 0.45W and 20W at 20K and 80K on the optimum operating conditions, respectively.

(4) A three-stage pulse tube refrigerator was designed, fabricated and tested. As the dead volume in the hot end of the three-stage pulse tube refrigerator was reduced, the cool-down characteristics in the cold end of the three-stage pulse tube refrigerator was improved. And the lowest no load temperature and the refrigeration capacity of the third stage cold end were 29.8K and 1.3W, 5W at 40K, 70K, respectively.

The lowest temperature of three-stage pulse tube refrigerator was higher than that of two-stage pulse tube refrigerator because three-stage pulse tube refrigerator was not yet optimized. There remains a lot of works to optimize the multi-stage pulse tube refrigerator to reach 4.2K.

ACKNOWLEDGMENT

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