Superconductivity and Cryogenics
Vol.12, No.4, (2010), pp.36~40

Research on fast cool-down of orifice pulse tube refrigerator by controlling orifice valve opening

Hyobong Kim[1], Jong-Ho Park[2,*]

[1] Energy Systems Research Division, Korea Institute of Machinery & Materials
[2] Department of Mechanical Engineering, Chungnam National University

Received 28 October 2010; accepted 19 November 2010

***Abstract*-- In this paper, a noble method for rapid cooldown of pulse tube refrigerator (PTR) was proposed and experimentally investigated. An orifice pulse tube refrigerator generates refrigeration effect by expansion PV work at the cold-end, and its amount is affected by the orifice valve opening. There exists the optimum valve opening for maximum cooling capacity and it varies as cold-end temperature. It is verified from simulation results using isothermal model that the optimum valve opening increases as the cold-end temperature increases. In the experiments, a single stage orifice pulse tube refrigerator is fabricated and tested. The fabricated PTR shows 97.5 K of no-load temperature and 10 W at 110 K of cooling capacity with the fixed orifice valve opening. From experiments, the initial cooldown curve with four cases of valve opening control scenario are obtained. And it is experimentally verified that the initial cooldown time can be reduced through the control of orifice valve opening.**

1. INTRODUCTION

A pulse tube refrigerator (PTR) is a small size cryocooler which is suitable for cryogenic cooling system of HTS (High Temperature Superconductor) applications such as SMES (Superconducting Magnetic Energy Storage), SFES (Superconducting Flywheel Energy Storage), HTS motor/generator, HTS cable.

A PTR in early stage of invention was insufficiently competitive with Stirling and GM cryocooler due to its low cooling performance and efficiency, although it has advantages of no moving part at cold section, simple configuration and low vibration. However, the performance of a PTR has been improved and now it can be a good substitution of Stirling and GM cryocooler [1, 2].

A PTR generates refrigeration effect by expansion PV work at the cold-end of pulse tube which is determined with the waveform of pressure and mass flow rate. Especially, the phase difference between pressure and mass flow rate is an important factor to determine the refrigeration effect. If the phase difference between two waveforms is 90 degree, there is no refrigeration effect in spite of the oscillation of pressure and mass flow rate. When two waveforms are in-phase, the refrigeration effect is maximized. Several methods for phase control were invented and now, various metering valves and gas reservoirs are used for phase control of PTR. An orifice PTR and double-inlet PTR are generally adopted for GM-type PTR [3, 4].

In the application of PTR to HTS system, a PTR cools down whole system to its operating temperature and absorbs generated and invaded heat during operation. In numerous cases, thermal mass of HTS system is the major cooling load to the PTR, and thus, it takes a few hours to a few days in initial cooling down process. Generally, a cryocooler including PTR is designed to show its best cooling performance at its operation condition. If a PTR is controlled to be optimized not only for its steady operation but also for its cool-down process, the cooldown time can be reduced. Some researches tried to reduce cooldown time with a PTR. Radebaugh et al. used variable reservoir volume to an inertance tube PTR and Pfotenhauer et al. used continuously variable inertance tubes [5, 6].

In this study, we propose a new method to reduce cooldown time of an orifice PTR. Fig. 1 shows the schematic diagram of a single stage orifice PTR. A helium compressor with a rotary valve generates pulsating pressure

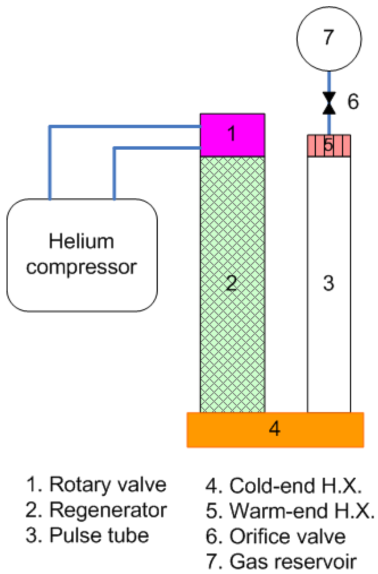


Fig. 1. Schematic diagram of single stage orifice pulse tube refrigerator.

* Corresponding author: jhpark@cnu.ac.kr

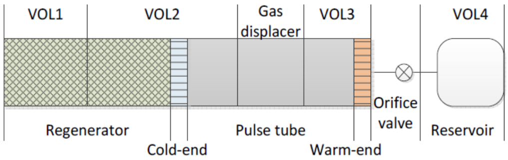


Fig. 2. Schematic diagram of isothermal model.

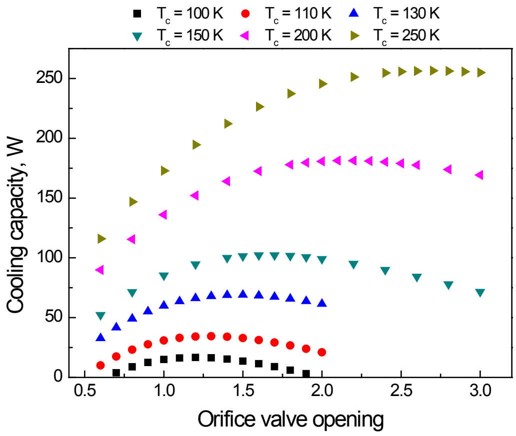


Fig. 3. Cooling capacity variation as orifice valve opening and cold-end temperature.

wave. An orifice valve and gas reservoir are incorporated as an phase control device. In the proposed method, the value of orifice valve opening is controlled during cooldown process.

In this paper, the tendency of cooling performance as the cold-end temperature is estimated using simple analysis model. In the experiments, a single stage orifice PTR is designed, fabricated and tested. The effect of valve control during cooldown process is investigated with the four cases of valve control scenario.

2. ANALYSIS

An isothermal model is used for the prediction of single stage orifice PTR [7, 8]. An isothermal model may overestimate the cooling capacity of a PTR because it contains many assumptions. But, it is useful to predict the behavior of a PTR due to its simplicity and fast calculation characteristics.

Fig. 2 shows the schematic diagram of isothermal model in this paper. A PTR is divided into the five sections and the mass conservation relations for the four sections of VOL1~VOL2 are solved and the pressure and mass flow rate at each section and interface using an ideal gas law and momentum conservation relation. The pressure drop through an orifice valve is expressed with eqn. (1). From the calculated waveform of the pressure at the pulse tube and the volume of the expansion space, the expansion PV power is calculated and then, the cooling capacity is calculated with eqn. (2). The ineffectiveness loss of regenerator is only considered as a thermal loss. In the analysis, the temperature at each section is assumed to be constant.

$$\dot{m} = C_{valve} \cdot \sqrt{P_1^2 - P_2^2} \quad (1)$$

$$\dot{Q}_{ref} = f \cdot \oint P_{pt} \cdot dV_e - \dot{Q}_{ineff} \quad (2)$$

where, C_{valve} : valve opening

f : operating frequency

P_{pt} : pressure of pulse tube

V_e : volume of expansion space

$\dot{Q}_{ref}$: ineffectiveness loss of regenerator

Fig. 3 shows the simulation results of the cooling capacity variation as orifice valve opening at various cold-end temperature. There exists the optimum value of orifice valve opening for the maximum cooling capacity for a certain cold-end temperature. When the orifice valve opening is larger than the optimum value, the amplitude of pressure and mass flow rate is small. On the contrary, when the orifice valve opening is smaller than the optimum value, the phase difference between pressure and mass flow rate reduces the cooling capacity. If the orifice valve opening extremely becomes to zero, the warm-end of pulse tube is closed and thus the PTR becomes to a basic type PTR.

From simulation results, the optimum orifice valve opening increases as the cold-end temperature increases. It is because the higher cold-end temperature causes the larger volume flow rate in the regenerator and pulse tube. The performance degradation for the smaller orifice valve opening is marked than for the larger orifice valve opening. From these results, it is expected that the valve control with the higher valve opening at the higher cold-end temperature can optimize the cooling capacity of a PTR at each cold-end temperature, and thus reduce cooldown time.

3. FABRICATION AND EXPERIMENTS

3.1. Fabrication of PTR

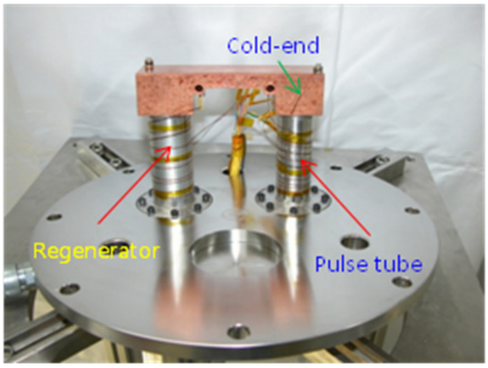
Table I shows the specifications of the fabricated single stage orifice PTR. The phosphorous bronze mesh of #200 was used for regenerating material, and a pair of metering valve (Swagelok, 4MG) was used as an orifice valve. Two metering valves were in parallel.

Fig. 4 shows photos of fabricated pulse tube refrigerator. The regenerator and pulse tube were connected with U-shape configuration. Temperature sensor (Lakeshore Inc., DT-670) and two cartridge heaters (Lakeshore Inc., HTR-25) were installed at cold-end heat exchanger for measuring temperature and loading heat, respectively. Warm-end heat exchanger is cooled by city water to prevent an excessive change of warm-end temperature. Helium compressor (Genesis vacuum technology 2.1) and rotary valve were used to generate pulsating pressure. The rotary valve is driven by stepping motor (Oriental motor, PK2913-02A).

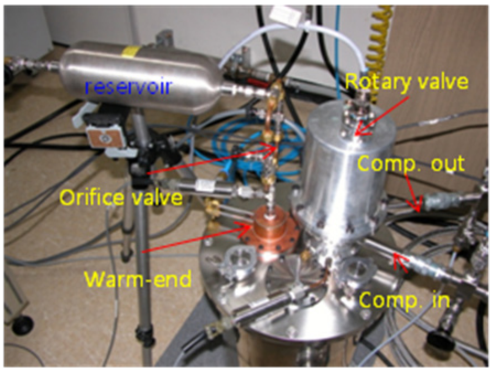
Fig. 5 shows the cross section of the cold-end. Its material is a pure copper. The copper mesh (#24) and the perforated copper plate are packed in the space of heat exchanging. The interior volume of each heat exchanging space are 5.7 cc for the regenerator side and 4.0 cc for the pulse tube side.

TABLE I
SPECIFICATIONS OF FABRICATED PULSE TUBE REFRIGERATOR.

Regenerator	ϕ 38.1, t 0.4, L 100 [mm] #200 phosphorous bronze mesh (twill, d_w = 52 μm, Number of screen = 780)
Pulse tube	ϕ 31.8, t 0.4, L 100 [mm]
Gas reservoir	1 L
Orifice valve	Swagelok metering valve (4MG + 4MG) Max. flow coeff. = 0.03[9]
Charging pressure	1.42 MPa
Operating frequency	4 Hz



(a) inside vacuum chabmber



(b) warm-part

Fig. 4. Photo of fabricated pulse tube refrigerator.

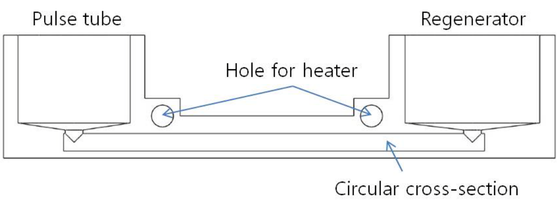
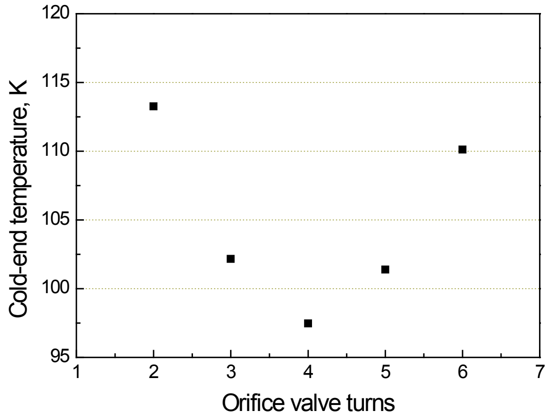


Fig. 5. Cross-section view of cold-end.

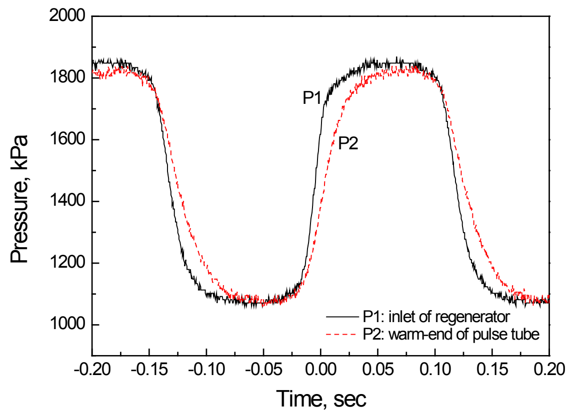
3.2. Cooling performance test

The basic cooling performance test of the fabricated PTR was performed with 1.42 MPa of charging pressure and 4 Hz of operating frequency. The experimental results are shown in Fig. 6.

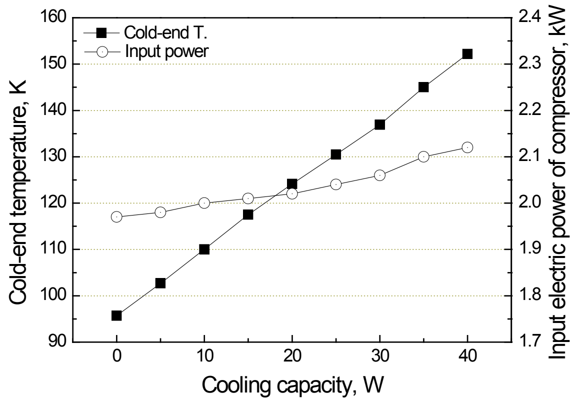
Fig. 6 (a) shows no-load temperature as orifice valve opening. In the experiment, two metering valves were used for orifice valve and opened with same valve turns. For example, the value of 4 in x-axis means that two metering



(a) no-load temperature as valve opening



(b) measurement of pressure waveform



(c) cooling capacity and compressor input power

Fig. 6. Experimental results of basic performance test.

valves were opened to 4 turns at the same time. The lowest no-load temperature was obtained with 4 turns of orifice valve and its value is 97.5 K. The pressure waveform at the inlet of regenerator and the warm-end with 4 turns of orifice valve open is shown in Fig. 6 (b).

With 4 turns of orifice valve open, the cooling capacity and compressor input power were measured as shown in Fig. 6 (c). The cooling capacity and cold-end temperature has almost linear relation and 152.2 K of cold-temperature was measured for 40 W of heat load. The input power of helium compressor was near 2 kW and slightly increases as heat load and cold-end temperature.

3.3. Effect of orifice valve control

With the four cases of valve control scenario, the initial cooldown curve was measured and compared. The opening of orifice valve was fixed during whole cooldown process in case 1. In case 2 ~ 4, the opening of orifice valve was manually controlled as cold-end temperature as shown in Fig. 7. The orifice valve was largely opened at the higher cold-end temperature. For all cases, the orifice valve turns were 4 turns at the end of cooldown process.

Fig. 8 shows the experimental results of initial cooldown curve for four cases. The initial cooldown characteristics are slightly affected by orifice valve control for whole cooldown process as shown in Fig. 8 (a). The final cold-end temperature for all cases was almost same.

Fig. 8 (b) shows the enlargement of mid period of cooldown process. For case 2, rapid cooldown was observed compared to the case of fixed orifice valve opening (case 1). Case 4 shows similar behavior with case 1, but case 3 shows slow cooldown. From fig. 8 (c), the time to reach to 100 K was measured. Their values were 2609, 2393, 2682, 2538 seconds for case 1 ~ 4, respectively. Although the effect of reducing cooldown time was small, it was experimentally verified that the rapid cooldown can be possible through orifice valve control during cooldown process. In this study, the optimum orifice valve opening as cold-end temperature was not clear and the valve control scenario was not optimized. If the valve control scenario is optimized, the more rapid cooldown can be possible. And, the effect of rapid cooldown by orifice valve control would become larger for the larger thermal mass of cooling target connected to the cold-end of a PTR.

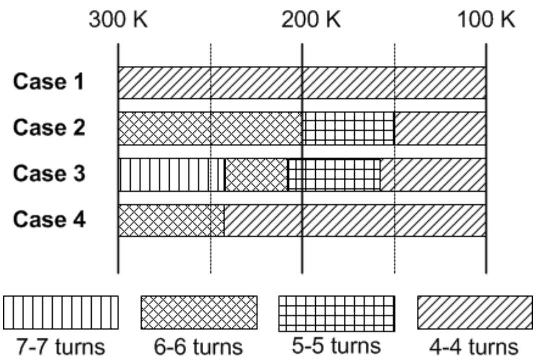
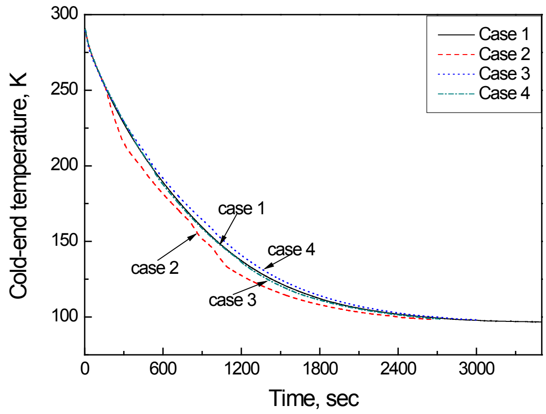
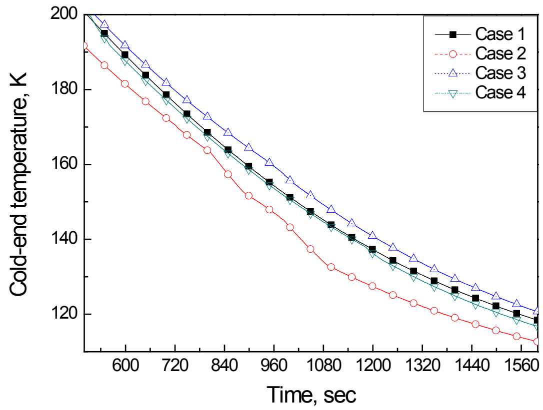


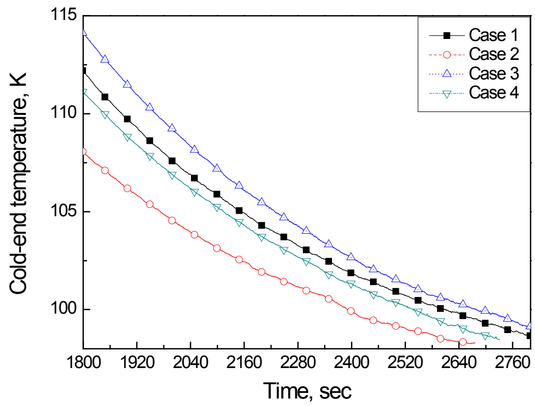
Fig. 7. Scenario of orifice valve control during initial cooldown process.



(a) whole cooldown period



(b) 500 ~ 1600 sec



(c) 1800 ~ 2800 sec

Fig. 8. Experimental results of initial cooldown curve.

4. CONCLUSIONS

From the analysis and experimental study of single stage orifice PTR with orifice valve control, followings can be concluded.

(1) From the simulation results, there exists the optimum orifice valve opening at a certain cold-end temperature and it increases as cold-end temperature increases.

(2) From the experimental results of basic cooling performance test with the fabricated single stage orifice PTR, the lowest temperature was 97.5 K and the cooling capacity was 10 W at 110 K.

(3) It was experimentally verified that the orifice valve control can reduce the initial cooldown time of a PTR.

(4) It is expected that the effect of rapid cooldown by through orifice valve control during cooldown process can be improved by the continuous control of orifice valve opening.

ACKNOWLEDGMENT

This work is supported by Korea Institute of Machinery & Materials and Ministry of Knowledge Economy.

REFERENCES

[1] H.J.M. ter Brake and G.F.M. Wiegerinck, “Low-power cryocooler survey,” *Cryogenics*, vol. 42, pp. 705-718, 2002.

[2] C. Wang, “Efficient 10 K Pulse Tube Cryocoolers,” *Cryocoolers* 13, pp. 133-140, 2005.

[3] G. Walker and E.R. Bingham, “Low-Capacity Cryogenic Refrigeration,” *Oxford: Clarendon*, pp. 145-153, 1994.

[4] Y. Luwei, Z. Yuan, L. Jingtao, “Research of pulse tube refrigerator with high and low temperature double-inlet,” *Cryogenics,* vol. 39, pp. 417-423, 1999.

[5] J.M. Pfotenhauer, T. Steiner, L.M. Qiu, “Continuously variable inertance tube refrigerators,” *Cryocoolers* 16 (in press), 2010.

[6] R. Radebaugh, A.O. Gallagher, M.A. Lewis, P.E. Bradley, “Proposed rapid cooldown technique for pulse tube cryocoolers,” *Cryocoolers* 14, pp. 231-240, 2007.

[7] A.J. Organ, “Stirling and Pulse-tube Cryo-coolers – The Inside Story,” *London: Professional Engineering Publishing*, 4.1-4.15, 2005.

[8] S.W. Zhu, Z.Q. Chen, “Isothermal model of pulse tube refrigerator,” *Cryogenics*, vol. 34, pp. 591-595, 1994.

[9] Swagelok catalog, http://www.swagelok.com/downloads/WebCatalogs/EN/MS-01-142.pdf.