Superconductivity and Cryogenics
Vol.14, No.4, (2012), pp.50~53

http://dx.doi.org/10.9714/sac.2012.14.4.050

Suppression of performance degradation due to cold-head orientation in GM-type pulse tube refrigerator

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Received 15 October 2012; accepted 19 November 2012

***Abstract*— This paper describes experimental study on GM-type pulse tube refrigerator (PTR). In a PTR, the pulse tube is only filled with working gas and there exists secondary flow due to a large temperature difference between cold-end and warm-end. The stability of secondary flow is affected by orientation of cold-head and thus, the cooling performance is deteriorated by gas mixing due to secondary flow. In this study, a single stage GM-type pulse tube refrigerator is fabricated and tested. The cooing performance of the fabricated PTR is measured as varying cold-head orientation angle and the results are used as reference data. Then, we divided interior space of pulse tube into three segments, and fixed the various size of screen mesh at interface of each segment to suppress the performance degradation due to secondary flow. For various configuration of pulse tube, no-load test and heat load test are carried out with the fixed experimental condition of charging pressure, operating frequency and orifice valve turns. From experimental results, the fine screen mesh shows the effective suppression of performance degradation for the large orientation angle, but the use of screen mesh cause the loss of cooling capacity rather than the case of no insertion into pulse tube. It should be compromised whether the use of screen mesh in consideration of the installation limitation of a GM-type pulse tube refrigerator.**

***Keywords*: GM-type pulse tube refrigerator, cold-head orientation, segmented pulse tube.**

1. INTRODUCTION

A pulse tube refrigerator (PTR) is a kind of small-scale regenerative cryocooler like GM or Stirling cryocooler. In those cryocooler, the refrigeration effect is generated by the expansion PV power which is produced by oscillation of a displacer at the cold-end. A PTR uses gas displacer which is the just gas element, whereas GM and Stirling cryocooler use solid displacer. They are classified with GM-type and Stirling-type as their mechanism of generating pulsating pressure. GM cryocooler and GM-type PTR use a helium compressor and rotary valve and, generally operates at low frequency. Stirling cryocooler and Stirling-type PTR are driven by a linear compressor and, have relatively high operating frequency.

A PTR has no moving part at its cold-part, and thus it has the characteristics of the simple configuration, low vibration and high reliability. But, it has the low cooling performance compared with GM cryocooler. Especially, there exists the secondary flow which deteriorates the cooling performance, because the pulse tube is filled with only working gas and it has large temperature gradient along axis.

In a PTR, the cooling performance is degraded as the cold-head orientation. Several previous researches analytically and experimentally showed that it results from the existence of secondary flow due to the gravity [1-4]. With a larger temperature difference, the gas space inside pulse tube is stable when the low temperature side is located below the high temperature side. On the contrary, if the low temperature side is located above the high temperature side, the secondary flow is activated and results in the performance degradation. Zhang et al. experimentally showed the suppression of the performance degradation by dividing space of pulse tube using screen mesh [5]. However, a Stirling-type PTR with 50 Hz of operating frequency was tested in their research. It is worth to investigate the suppression effect for GM-type PTR, because it is more strongly affected by the gravity due to its low operating frequency.

In this study, we fabricated the single stage GM-type pulse tube with an orifice valve and gas reservoir as a phase control device. The screen mesh was used to suppress the orientation dependence and the cooling performance was measured for several orientation angle. Especially, the effect of screen mesh size is deeply discussed.

2. EXPERIMENTS

2.1. Experimental Setup

We fabricated the single stage GM-type pulse tube

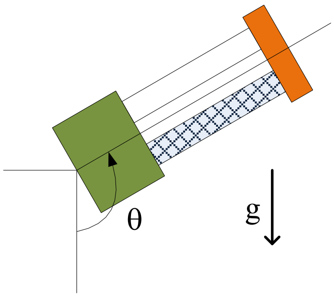

Fig. 1. Definition of orientation angle.

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TABLE I
SPECIFICATIONS OF THE FABRICATED PTR.

Regenerator	• 38.1 (O.D.), 0.4 (t), 150 (L) [mm] • #200 phosphorous bronze mesh
Pulse tube	• 3.18 (O.D.), 0.4 (t), 150 (L) [mm]
Gas reservoir	• 1 liter of internal volume

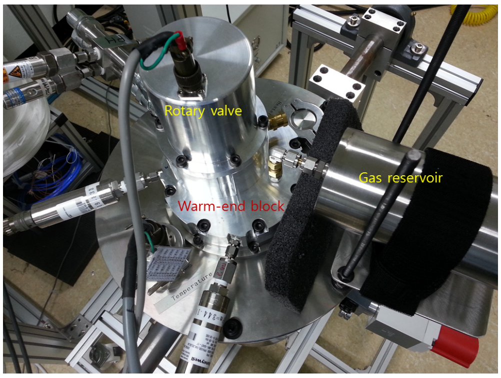


Fig. 2. Warm-part of the fabricated PTR.

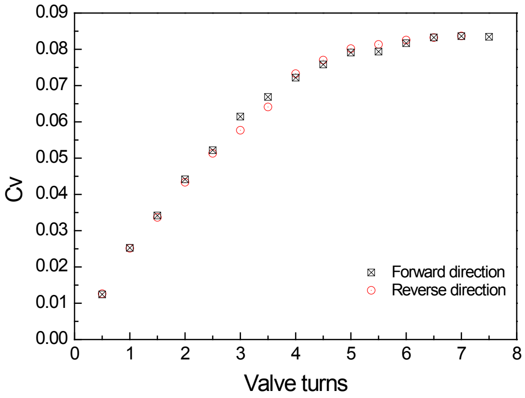
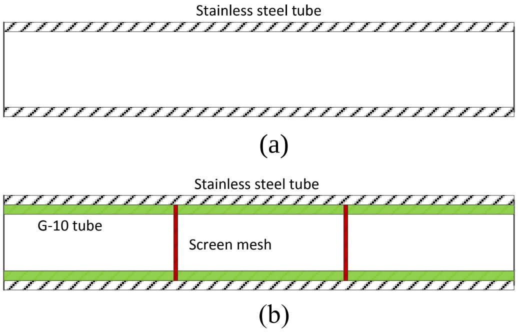


Fig. 3. Measured flow coefficient of the fabricated orifice valve.



(a)

(b)

Fig. 4. Cross-section view of pulse tube, (a) reference : empty tube, (b) fixed screen mesh with inserted G-10 tube.

refrigerator. It has U-shape configuration and the orientation angle defined as shown Fig. 1. The specification of the fabricated PTR is described in Table I. Diameter of regenerator and pulse tube is 38.1 and 31.8 mm, respectively. They have same length of 150 mm and wall thickness of 0.4 mm. The phosphorous screen mesh of #200 is used as regenerating material. Fig. 2 shows the warm-end block of the fabricated PTR. The rotary valve assembly except the driving motor, the warm-end heat exchanger and the orifice valve are integrated in it. In the fabricated PTR, an orifice vale is also fabricated and its flow coefficient is experimentally measured as shown in Fig. 3.

Fig. 4 shows the cross-section view of the pulse tube. First, the empty pulse tube is tested and the measured cooling performance is used as reference data in this study. Then, we divided the pulse tube with three sections and inserted the screen mesh at the interface of sections. Three segments of thin G-10 tube are inserted into the pulse tube to fix the screen mesh.

2.2. Experiments

In experiments, the cooling performance tests are carried out for three different configurations of the pulse tube. One is no screen mesh inserted, the other is only G-10 tube inserted and the last is the screen mesh inserted. Five different size of screen mesh are used in this experiment. For each screen mesh size, two screens are fixed at each interface of the segmented G-10 tube. The size and material of used screen mesh are summarized in Table II.

In the cooling performance test, no-load test and heat load test are performed in same conditions of charging pressure, operating frequency, orifice valve turns for all configurations of pulse tube. Each value is 1.6 MPa, 3.0 Hz and 0.5 turns, respectively.

In no-load test, no-load temperature is measured for the orientation angle of 0, 30, 60, 90, 120, 150, 180 degrees. In heat load test, the orientation angle is fixed with 0 degree and cold-end temperature is measured as applied heat load.

3. RESULTS AND DISSUSSIONS

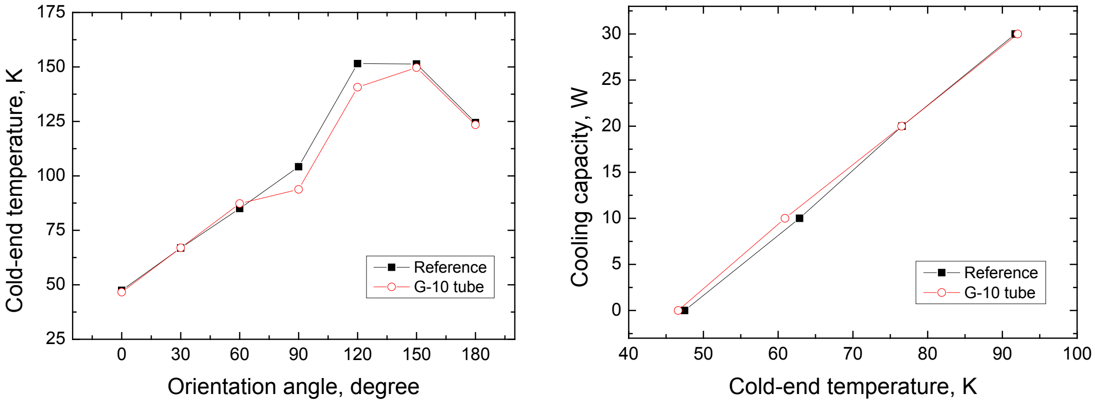
3.1. Effect of G-10 Tube Insertion

Fig. 5 shows the effect of G-10 tube insertion. There is no significant difference except a few points. It is thought that difference for 90^{o} and 120^{o} results from the variation of warm-end cooling condition including surrounding temperature. From the results, it is confirmed that G-10 tube can fix the screen mesh without affecting cooling performance.

Fig. 5 (a) reveals the dramatic degradation of cooling performance in GM-type PTR due to the cold-head orientation. Especially, it is remarkable in the range of 120 ~ 150 ^{o}. No-load temperature dramatically increases up to

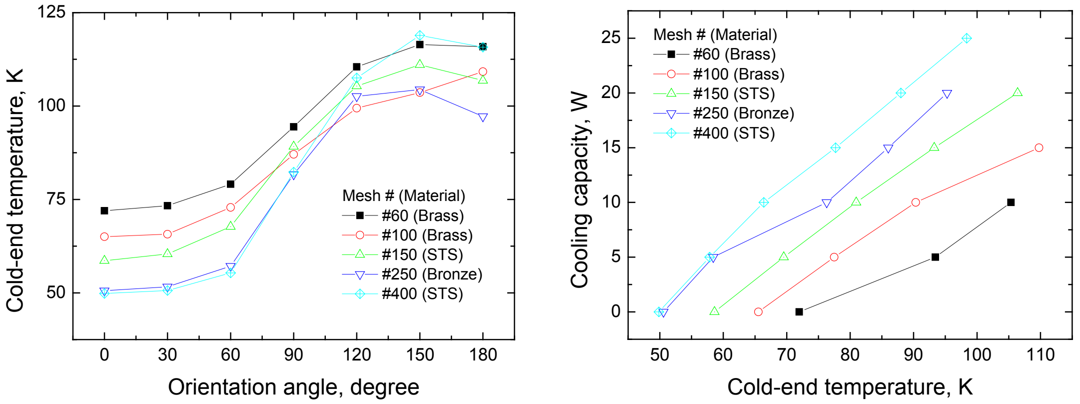
TABLE II
SIZE AND MATERIAL OF USED SCREEN MESH.

Screen mesh	
Size (Mesh #)	Material
#60	Brass
#100	Brass
#150	Stainless steel
#250	Phosphor bronze
#400	Stainless steel



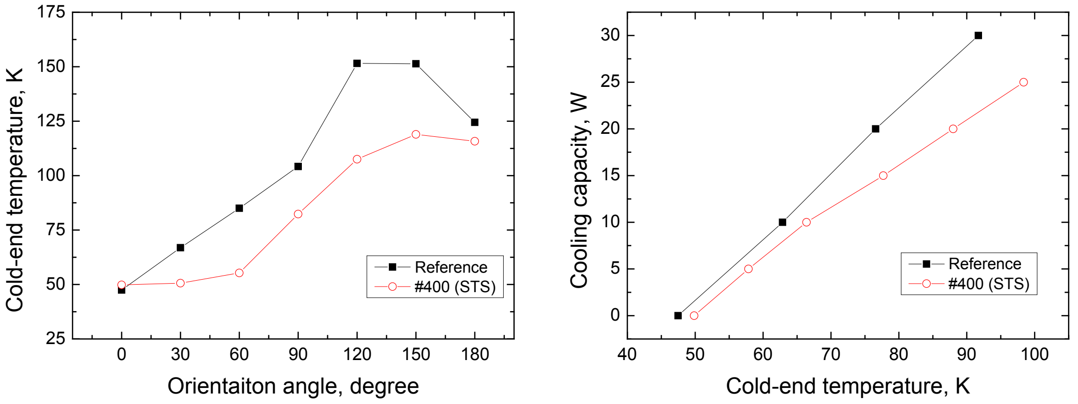
(a) (b)

Fig. 5. Effect of G-10 tube insertion. (a) results of no-load test, (b) results of heat load test.



(a) (b)

Fig. 6. Effect of screen mesh size. (a) results of no-load test, (b) results of heat load test.



(a) (b)

Fig. 7. Comparison results with and without screen mesh. (a) results of no-load test, (b) results of heat load test.

151.5 K for 120 ° of orientation angle, whereas it is 47.8 K for 0 °. This behavior coincides with the results from the previous researches, but shows further severe pattern. A PTR generates refrigeration work with gas expansion by gas displacer in the pulse tube which is only filled with working gas. The stability of flow inside pulse tube is affected by the orientation of cold-head and thus, cooling performance is deteriorated by gas mixing due to secondary flow.

When, the orientation angle is 0 ° the cold and dense gas element is located below the warm and less dense gas element. In this situation, the gas element is stable and the pulsating pressure driven gas flow is dominant. Whereas, the gas element is mixed in the inclination of pulse tube by the secondary flow which is caused by the density difference. The gas mixing is more activated with the increase of orientation angle except the case of 180 °. The cooling performance of the inclined pulse tube refrigerator is determined by the complex effects of pulsating pressure driven flow and secondary flow, and shows the worst performance for 120 ° ~ 150 ° of orientation angle.

3.2. Effect of Screen Mesh Size

Fig. 6 shows the variation of the cooling performance as screen mesh size. It is observed the suppression of the performance degradation over 60 ° of the orientation angle. The cooling performance of the PTR is less affected by the orientation angle for 0 ° and 30 °. In those conditions, the similar no-load temperature with the reference case (no insertion in the pulse tube) is obtained for the fine mesh, whereas the higher no-load temperature is measured for the coarse mesh. In the pulse tube, gas element plays a role of displacer and the uniform flow is required for the good performance. The uniformity of the gas flow is deteriorated with passing through the coarse screen mesh. From the results of Fig. 6 (a), the use of the finer mesh rather than #250 mesh is required for preventing the performance degradation due to the use of screen mesh. It is shown a little complicated trend as the variation of mesh size over 90 ° of orientation angle. It shows the different optimum mesh size for suppressing the orientation effect of the PTR for each orientation angle. From the results, it is obvious that the use of screen mesh for dividing space is effective to suppress the performance degradation due to the cold-head orientation. But, it also causes the non-uniformity of gas flow and the interruption of the pulsating pressure driven flow. For the small orientation angle, the non-uniformity of gas flow decreases as increasing mesh size. Whereas, it is thought that the interruption of pressure driven flow more strongly appears with the fine mesh for the large orientation angle. The effect of mesh size on the cooling capacity at 0 ° orientation angle is clear. The coarser mesh results in the worse cooling capacity as shown in Fig. 6 (b).

The results of Fig. 6 show that the suppression of performance degradation with using screen mesh is not effective for the large orientation angle in GM-type PTR like as Stirling type PTR. It is because GM-type PTR operates with low frequency of a few Hz and thus, is more strongly affected by the secondary flow.

Fig. 7 shows the comparison between the reference case and the case of #400 mesh used. The suppression of the performance degradation is clearly observed for all orientation angle. There is no significant variation in no-load temperature up to 60 ° of orientation angle, but it still shows the large performance degradation for the higher orientation angle. From the results of heat load test, the cooling capacity at same cold-end temperature slightly decreases with using screen mesh. Especially, the difference increases for the higher cold-end temperature.

4. CONCLUSIONS

In this study, it is experimentally investigated the suppression effect of the performance degradation due to the cold-head orientation in GM-type pulse tube refrigerator. From the results, followings can be concluded.

(1) The performance degradation increases as increasing the orientation angle of cold-head in GM-type pulse tube refrigerator. Especially, it is dramatic over 90 □ of orientation angle.

(2) By using the screen mesh for dividing inside pulse tube, it can be suppressed the performance degradation due to the secondary flow caused by the cold-end orientation. The better cooling performance for the finer mesh is observed under 90 ° of orientation angle, and there exists the optimum mesh size for each orientation angle over 90 °.

(3) The use of screen mesh results in the decreases of the cooling capacity rather than the case of no insertion, although it can successfully suppress the performance degradation due to the cold-end orientation. It is thought that the user or designer of a GM-type pulse tube refrigerator should decide the use of screen mesh as installation limitation of a cryocooler.

(4) The experimental results in this study reveals that the use of screen mesh is effective to suppress the performance degradation due to the cold-head orientation for the small orientation angle, but it also causes the decreases of cooling performance. It is required the study on the optimization of the mesh size, number of screen mesh, and number of segments.

ACKNOWLEDGMENT

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

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