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COOLING CHARACTERISTICS OF A MODIFIED MINIATURE PULSE TUBE REFRIGERATOR

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ABSTRACT

The cooling performance of a split type miniature pulse tube refrigerator with a flexure spring compressor was investigated. The diameter and length of the miniature pulse tube were 5 mm and 60 mm, respectively. A stack of stainless steel mesh of #300 was used as a regenerator. An Oxford type compressor was driven at frequencies from 40 to 55 Hz with a swept volume of 1-2 cm³. The lowest temperature of 99.6 K with no load was achieved for an input power of 30 W at a filling pressure of 1.32 MPa. The compressor back-side volume was used as a reservoir and capillary tubes were used instead of double inlet and orifice needle valves. The influence of orifice capillary tube length on the cooling performance of the miniature pulse tube refrigerator was investigated.

INTRODUCTION

In a previous report¹ on a miniature split type pulse tube refrigerator, a cooling power of 0.16 W at 195 K for an input power of 6 W was reported. For approaching the final target of 1 W at 80K for 30 W input power, a refrigerator was redesigned mainly to reduce the void volume in a system. Two needle valves for double inlet and orifice valves were removed and capillary tubes were used² for less void volume and more effective phase shifting between pressure and displacement of the working gas. Compressor back-side volume was used for a buffer reservoir as in the previous system.

The cooling performance of an orifice and double inlet pulse tube refrigerator was studied by varying frequencies from 40-55 Hz in a filling pressure range of 1.3-1.8 MPa. The compressor piston position was well regulated by adding DC bias current so as to apply an input power of over 30 W. The lowest temperature dependencies on the length of capillary tube, frequency and filling pressure were investigated.

MINIATURE PULSE TUBE REFRIGERATOR

A so-called Oxford type compressor which was designed and fabricated in our laboratory³ was used for this experimental research. Main parameters of the refrigerator are listed in Table 1. More detailed parameters of the refrigerator were mentioned in a previous paper, and information on hardware and operating conditions are also listed in Table 2.

Table 1. Main parameters of the miniature pulse tube refrigerator.

Parameters	Details
Compressor	Linear drive with flexure spring
Resonance frequency	49 Hz at $P = 1.5$ MPa
Comp. swept volume	1-2 cc
Pulse tube	5 mm ϕ i.d. X 60 mm, $V = 1.2$ cc
Regenerator	8 mm ϕ i.d. X 55 mm, $V_{\text{void}} = 1.8$ cc #300 SUS mesh X 700

Table 2. Hardware and operating conditions.

Hardware	Details
Double inlet	Capillary tube (0.7 mm ϕ i.d. X 40 mm)
Orifice	Capillary tube (0.4 mm ϕ i.d. X 25, 50 cm)
Buffer	400 cc (compressor back volume)
Operating condition	
Frequency	40- 60 Hz
Pressure	1.3-1.8 MPa
Pressure ratio	~ 30 W
Input power	1.2-1.3
Piston position control	DC bias current

Figure 1 shows a schematic diagram of the refrigerator. A compressor, regenerator and pulse tube are connected by fine copper tubes of 1/8 inch in diameter and 0.5 mm in thickness. Compressor discharge pressures were monitored by pressure sensor (PMS30H bulk-type semiconductor) with an accuracy of a few percent. The displacement of the compressor piston was monitored by a Linear Variable Differential Transformer (LVDT) position sensor. Cold head temperature was monitored by a silicon diode thermometer (SMDT⁴) with an accuracy of ± 0.5 K. There is no radiation shield between the cold head and a vacuum housing. During the experiment, a vacuum housing was connected to the high vacuum pump. Figure 2 shows a detailed draw of pulse tube and regenerator. Figure 3 shows a photograph of the compressor and cold head with a vacuum jacket.

Figure 1. General arrangement of the miniature pulse tube refrigerator. **Figure 2.** Miniature pulse tube and regenerator.

Figure 3. Photograph of the miniature pulse tube refrigerator with a flexure spring compressor.

COOLING PERFORMANCE

The system was evacuated and filled with grade-A pure helium gas up to 1.3-1.8 MPa. The compressor was then operated at frequencies around 50 Hz. The input power to the compressor, Q_{IN} , was kept around 30 W. The compressor p-v work on working gas, Q_{PV} , was obtained by calculating the net area of the compressor p-v plane diagram. As the inner diameter and length of double inlet capillary was fixed, three parameters were varied. Those are frequency, filling pressure and the length of orifice capillary tube.

Cool down

Figure 4 shows the typical cool down characteristics when the refrigerator was operated at 50 Hz with a filling pressure of 1.32 MPa.

Figure 4. Cool down characteristics.

Cooling speed is also shown in the figure. These data were obtained with a double inlet and orifice configuration using capillary tubes. Detailed information about the capillary tubes is given in Table 1.

Frequency dependence

The relationships between frequencies and the lowest temperature achieved are shown in figure 5. The influence of orifice capillary tube length and filling pressure on achieved temperature are also shown in the figure. Compressor input power was kept at 31.5 W, but the piston stroke varied from 4.6 to 5.8 mm. Its variation depended on filling pressure and frequency when the length of orifice capillary tube was same. Increasing the filling pressure results in a decreasing piston stroke. Also, increasing operating frequency results in a decreasing the piston stroke.

The lowest temperature was obtained at a filling pressure of 1.32 MPa with an operating frequency of 50 Hz and when the length of orifice capillary was 25 cm. However, when the compressor was driven at an input power of 15 W, the lowest temperature was obtained at a filling pressure of 1.51 MPa, not at 1.32 MPa even with the same capillary length. The typical wave form of the compressor delivery pressure, piston displacement and swept volume of compressor are shown in Figure 6. The compressor p-v diagram at 45 Hz, 50 Hz and 55 Hz is also shown in the figure.

Filling pressure dependence

Figure 7 shows filling pressure influence on the lowest temperature. The compressor pressure ratio, defined as P_{MAX}/P_{MIN} , and compressor efficiency, defined as Q_{PV}/Q_{IN} , are also shown in the figure. The operating frequency was 50 Hz, the length of orifice capillary was 25 cm and compressor input power was kept at 31.5 W. A much lower temperature was achieved when the filling pressure was decreased. The maximum pressure ratio was 1.33 at a filling pressure of 1.31 MPa, and the maximum compressor efficiency of 69.5% was obtained at a filling pressure of 1.51 MPa.

The filling pressure was decreased to 1.18 MPa. However, noise came from the compressor and an input power of more than 28 W could not be applied. The lowest temperature for this condition was 103 K.

Figure 5. Frequency dependence of lowest temperature at $Q_{in} = 31.5$ W. Filling pressure and length of orifice capillary are varied (25 and 50 cm) to investigate those influences.

Figure 6. Typical wave form of the compressor delivery pressure, piston displacement and swept volume of compressor in a p-v diagram.

Figure 7. Filling pressure influence on the lowest temperature. The compressor pressure ratio and compressor efficiency are also shown.

Figure 8. Achieved lowest temperature versus compressor input power at filling pressures of $P=1.59$ and 1.87 MPa .

Input power dependence

Figure 8 shows the compressor input power dependence on the lowest temperature at filling pressures of 1.59 and 1.87 MPa . The operating frequency is 50 Hz , and the orifice capillary length is 25 cm with a double inlet configuration.

Figure 9. Lowest temperature versus the pressure ratio of pulse tube refrigerator. Results of Stirling refrigerator by same compressor is also shown.

Pressure ratio dependence

Figure 9 shows the pressure ratio dependence on the lowest temperature. For all cases, the refrigerator configuration is the same (capillary double inlet tube and orifice capillary tube of 25 cm in length). Various pressure ratios were obtained by changing the filling pressure, input power and piston position control by using DC bias current. Data for the Stirling refrigerator using the same compressor are also shown in the figure for comparison.

In the case of the miniature pulse tube refrigerator, the temperature could not be lowered even if the pressure ratio was increased from 1.26 to 1.33. Under the same compressor operating conditions using the same compressor system, the Stirling refrigerator achieved a lowest temperature of 50 K, which is 50 degrees lower than that of miniature pulse tube refrigerator.

SUMMARY

Cooling characteristics of a miniature pulse tube refrigerator, a split-type with a flexure spring compressor, and with capillary tubes for double inlet and a orifice valves were investigated. The lowest temperature of 99.6 K was achieved for a compressor input power of 30 W. The optimum length of orifice capillary tube was found to be 25 cm for 0.4 mm ϕ i.d. at a frequency of 50 Hz and a filling pressure of 1.32 MPa. A simple DC bias current method worked well for piston position control for large piston displacement. Even when the pressure ratio is close to that of Stirling refrigerator, the achieved lowest temperature by the pulse tube refrigerator is 50 degrees higher than the Stirling refrigerator. Thus, cooling mechanism and losses peculiar to the miniature pulse tube refrigerator should be investigated.

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