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PERFORMANCES OF SINGLE AND TWO-STAGE PULSE TUBE CRYOCOOLERS UNDER DIFFERENT VACUUM LEVELS WITH AND WITHOUT THERMAL RADIATION SHIELDS

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ABSTRACT

Single and two-stage Pulse Tube Cryocoolers (PTC) have been designed, fabricated and experimentally studied. The single stage PTC reaches a no-load temperature of ~ 29 K at its cold end, the two-stage PTC reaches ~ 2.9 K in its second stage cold end and ~ 60 K in its first stage cold end. The two-stage Pulse Tube Cryocooler provides a cooling power of ~ 250 mW at 4.2 K. The single stage system uses stainless steel meshes along with Pb granules as its regenerator materials, while the two-stage PTC uses combinations of Pb along with Er_3Ni / $HoCu_2$ as the second stage regenerator materials. Normally, the above systems are insulated by thermal radiation shields and mounted inside a vacuum chamber which is maintained at high vacuum. To evaluate the performance of these systems in the possible conditions of loss of vacuum with and without radiation shields, experimental studies have been performed. The heat-in-leak under such severe conditions has been estimated from the heat load characteristics of the respective stages. The experimental results are analyzed to obtain surface emissivities and effective thermal conductivities as a function of interspace pressure.

KEYWORDS: Pulse Tube, Cryocooler, Regenerator, Gas conduction, Radiation, Emissivity

INTRODUCTION

The area of Cryocoolers such as Gifford McMahon (GM), Stirling, Pulse Tube etc have witnessed significant developments over the last few decades. Of these, the PTC offer significant advantages of low vibration levels, higher reliability for long term performance by the absence of moving parts at cryogenic temperatures.

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Since the discovery of Pulse Tube refrigeration in 1964 by Gifford and Longsworth [1], several developments [2-6] have occurred resulting in commercial PTCs in the market. However, research is still active in this area to understand the fundamental cooling mechanisms which might lead to technological breakthroughs.

In our laboratory, we have developed both single and two-stage GM type Pulse Tube Cryocoolers. The single stage PTC reaches a no-load temperature of ~ 29 K at its cold end, while the two-stage PTC reaches ~ 2.9 K in its second stage cold end and ~ 60 K in its first stage. The two-stage PTC provides a cooling power of ~ 250 mW at 4.2 K. Normally, the above systems are insulated by thermal radiation shields and mounted inside a vacuum chamber which is maintained at high vacuum. However, it is also important to know the performances of these Pulse Tube Cryocoolers in the adverse conditions such as loss of vacuum in the interspace with or without superinsulation for different practical applications. In this work, we have studied these on single and two-stage PTCs and the observed experimental results are presented here.

DETAILS OF EXPERIMENTAL SETUP

FIGURE 1(a) shows the schematic of the single stage PTC, while FIGURE 1(b) shows that of the two-stage PTC. The Pulse Tubes and regenerator housings consist of thin walled stainless steel tubes (wall thickness ~0.5mm). The regenerators of single stage system and that of the first stage of the two-stage system are fabricated using stainless steel meshes (size 200) and Pb granules (~250 µm average grain size) to about 15% in the cold end. On the other hand, combinations of Pb with Er_3Ni / $HoCu_2$ in different volume percentages are used as the second stage regenerator materials for the two-stage PTC. The room temperature seals are made by o-rings and the low temperature seals are made with indium. More details on the heat exchanger design, needle valves used, temperature and pressure sensors, data acquisition etc are described in reference [7].

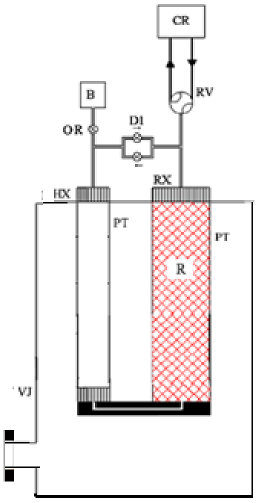

FIGURE 1(a). Schematic of the single stage PTC

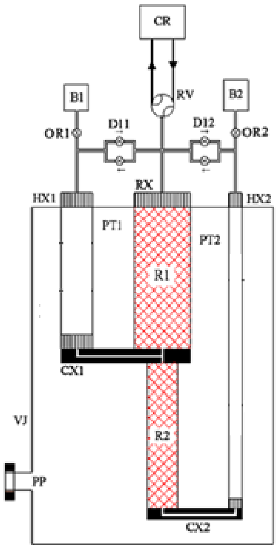

FIGURE 1(b). Schematic of Two-stage PTC.

HX – Heat Exchanger at PT hot end, CX – Heat Exchanger at PT cold end, RX – Heat Exchanger at regenerator hot end, DI – Double-inlet valve, OR – Orifice valve, RV- Rotary valve, B – Buffer volume, CR – Compressor, PP – Evacuation port, VJ – Vacuum jacket, PT – Pulse Tube, R – Regenerator. The numbers '1' and '2' in figure correspond to the respective components at 1st stage and the 2nd stage in the system

TABLE 1. Details of dimensions and cold end temperatures of the single and two-stage Pulse Tube Cryocoolers

<table>
<tr><td colspan="10">PT – Pulse Tube, Reg – Regenerator, D- Diameter, L – Length, SS – Stainless steel meshes (size 200). First stage Regenerator is ss meshes (85%) + Pb (15%).. 2nd stage regenerator is Er_3Ni (30%), $HOCu_2$ (30%), Pb (30%) separated by SS meshes. All dimensions are in mm.</td></tr>
<tr><td colspan="10">Single Stage PT Cryocooler</td></tr>
<tr><td colspan="2">PT</td><td colspan="4">REG</td><td colspan="4">No Load Temperatures (K)</td></tr>
<tr><td>D</td><td>L</td><td colspan="2">D</td><td colspan="2">L</td><td colspan="4" rowspan="2">29 K</td></tr>
<tr><td>19</td><td>270</td><td colspan="2">25</td><td colspan="2">200</td></tr>
<tr><td colspan="10">Two stage PT Cryocooler</td></tr>
<tr><td colspan="4">1st stage</td><td colspan="4">2nd stage</td><td colspan="2">No Load Temperatures (K)</td></tr>
<tr><td colspan="2">PT</td><td colspan="2">REG</td><td colspan="2">PT</td><td colspan="2">REG</td><td>1st Stage</td><td>2nd stage</td></tr>
<tr><td>D</td><td>L</td><td>D</td><td>L</td><td>D</td><td>L</td><td>D</td><td>L</td><td rowspan="2">59.5</td><td rowspan="2">2.9</td></tr>
<tr><td>19</td><td>270</td><td>25</td><td>200</td><td>14</td><td>390</td><td>19</td><td>190</td></tr>
</table>

The instrumented PTC is loosely surrounded with 10 layers of superinsulation (radiation shields). In the case of the single stage PTC, its cold head and the regenerator are insulated. On the other hand, for the two-stage PTC, initially, the second stage cold head and its regenerator are insulated. Subsequently, the first stage cold head and its regenerator are insulated, with overlapping to the second stage. The insulated PTC is mounted in the vacuum jacket and evacuated by a turbo molecular pumping system. Experiments conducted on PTCs insulated with thermal radiation shields in high vacuum in the interspace serve as the bench marks for the evaluation of the systems with or without superinsulation and with varying interspace vacuum levels.

EXPERIMENTAL RESULTS

The best configurations of the single and two-stage Pulse Tube Cryocoolers have been used in our present studies. TABLE 1 gives the details of the PTCs namely their dimensions, materials used for regenerators and cold end temperatures etc. In further discussions, the single stage PTC with and without radiation shields is designated as SSPTC1 and SSPTC2 respectively. Similarly, the two-stage PTC with and without radiation shields are designated as TSPTC1 and TSPTC2 respectively.

Cooldown Characteristics

FIGURE 2(a) plots the cooldown characteristic of the single stage Pulse Tube cryocoolers, with and without radiation shields but with high vacuum in the interspace. Similar results are shown in FIGURE 2(b) for the two-stage PTC. It is observed from the above figure that the lowest temperatures of 29 K and 44 K are obtained for single stage PTCs with and without radiation shields respectively. The cool-down time of SSPTC1 is found to be more than that of SSPTC2 and this is due to the additional thermal mass of the insulation.

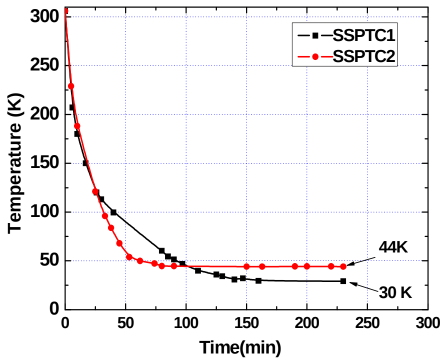

FIGURE2 (a). Cooldown of Single stage PTCs

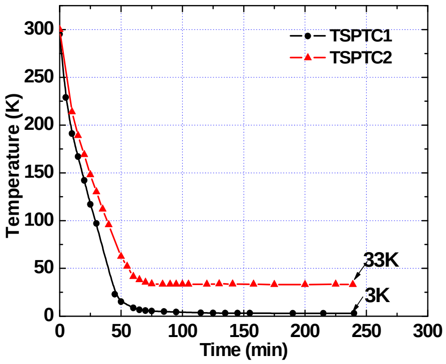

FIGURE 2(b). Cooldown of two stage PTCs

Since the radiation shields are wound loosely, we can assume that the conduction heat transfer within the insulation is negligible. Hence, the comparison of the above configurations indicates that SSPTC2 has the additional radiation heat transfer over that of SSPTC1, while the solid and gas conduction heat transfers are the same for both. To estimate this additional heat transfer to the single stage PTC, the heat load characteristics of SSPTC1 can be used. Similar situation is applicable for the two-stage PTCs.

Cooling Power Characteristics

The cooling power characteristics of the single stage Pulse Tube Cryocooler SSPTC1 and the two-stage Pulse Tube Cryocooler TSPTC1 are shown in FIGURES 3(a) and 3(b) respectively. Curve fitting the experimental data can be used to calculate the heat load on the system at any other temperature.

Analysis of Radiation Heat Transfer

The difference in radiation heat transfer between the two configurations SSPT1 and SSPT2 can be written as,

$$\Delta Q_r = \sigma A_1 \varepsilon_{12} F_{12} (T_2^4 - T_1^4) - \sigma A_1 F_{12} (\varepsilon_{sh} / n)(T_2^4 - T_1^4) \qquad (1)$$

Here ε_{12} refers to the effective emissivity between cold and warm surfaces and is given by the equation

$$(1/\varepsilon_{12}) = \left[(1/\varepsilon_1) + (A_1 / A_2)(1/\varepsilon_2 - 1)\right]^{-1} \qquad (2)$$

Where ε_1 and ε_2 are the emissivities of the cold and warm surfaces and ε_{sh} is the emissivity of the radiation shield. A_1 is the cold surface area, F_{12} is the configuration factor (equals to unity in the present case). T_2 and T_1 are the temperatures of warm and cold surfaces respectively. Since there exists a temperature gradient from the cold head to the room temperature through the pulse tube and the regenerator, equation (1) is only a generalized expression for the estimation of the radiation heat transfer and A_1 is not just the cold end surface area.

Now, the total pulse tube system is divided into several smaller segments of average temperature, and the radiation heat transfer is estimated by the above equation by summing over these segments. The temperature gradients across the Pulse Tubes and the regenerators are arrived at by earlier experimental data and the number of segments is chosen to be high to minimize the errors. A simple program written in Fortran was used to calculate ΔQ_r . From FIGURE 3(a), ΔQ_r is estimated as ~ 5.18W.

Since the ε_{sh} is very small, the second term of equation (1) can be neglected. Introducing the surface areas of the cold end, the Pulse Tube and the regenerator in this equation, an average effective emissivity of ~ 0.2968 is obtained for the cold and warm surfaces of the PT cooler. For the case of the two-stage PTCs, the difference in the radiation heat load is estimated as $\Delta Q_r = 5.40$ W. Based on the calculations similar to that of the single stage system, an average emissivity of 0.3260 is obtained for the warm and cold surfaces of the PTC, indicating a good agreement with the values obtained for the single stage PTC.

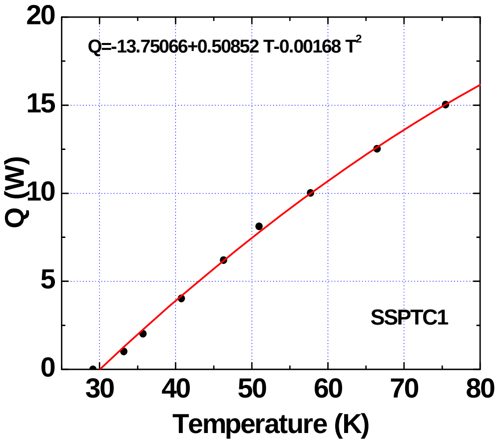

FIGURE 3(a). Cooling power characteristics of single stage Pulse Tube Cryocooler

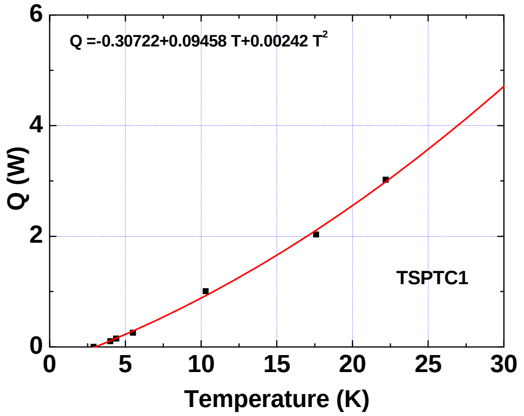

FIGURE 3(b). Cooling power Characteristics of the two-stage Pulse Tube Cryocooler

Analysis of gas conduction heat transfer

Experimental studies have been conducted for the configurations SSPTC1 and TSPTC1 varying interspace pressure levels. Using the cooling power characteristics of these systems, the data is converted to heat load on the Pulse Tube Cryocooler as a function of interspace gas pressures.

In the case of single stage PT cryocoolers, both helium and air have been used as the interspace gas. The gas conduction heat transfer depends on the interspace gas pressure. It is proportional to gas pressure in the free molecular flow regime, and nearly constant in the continuum regime. The gas conduction heat transfer in the free molecular flow regime can be written as [8-9],

$$Q_{gc} = ((\gamma+1)/(\gamma-1))(R/8\pi MT)^{1/2}\alpha A_1 P(T_2 - T_1) \tag{3}$$

Here γ is the ratio of specific heats, R is the universal gas constant, M is the molecular weight of gas, α is the overall accommodation coefficient, P is the interspace gas pressure. Here again, as mentioned earlier in respect of radiation heat transfer, A_1 is not just the cold end surface area. As before, the total pulse tube system is divided into several smaller segments of average temperature, and the gas conduction heat transfer is estimated by the above equation by summing over these segments by a simple program written in Fortran. To understand these experimental results, we plot the effective thermal conductivity k_{eff} as a function of pressure. k_{eff} is given by the equation

$$k_{eff} = Qd/(A_1(T_2 - T_C)) \tag{4}$$

Here d is the insulation thickness, which is obtained by knowing the average outer diameter of the system after applying the superinsulation. T_C is the temperature of the cold end. The results are shown in FIGUREs 4(a) and 4(b) for SSPTC1 and TSPTC1 respectively. FIGURE 4(a) shows that k_{eff} is higher when helium is used as interspace gas.

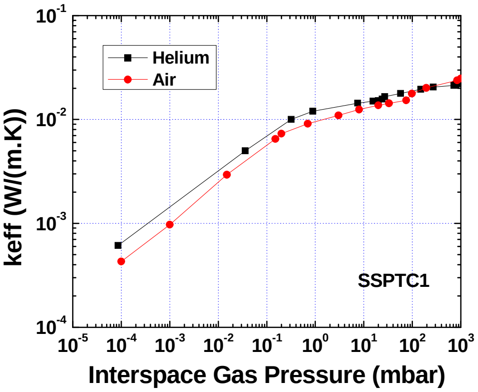

FIGURE 4(a). Plot of effective thermal conductivity versus interspace gas pressure for single stage PTC

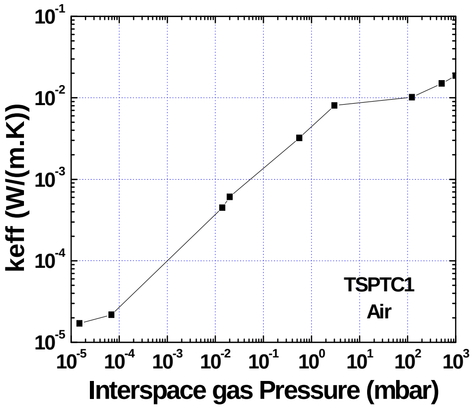

FIGURE 4(b). Plot of effective thermal conductivity versus interspace gas pressure for two-stage PTC

It is observed that k_{eff} has a power law variation with respect to pressure at low pressures and becomes nearly constant at higher pressures. However, at very higher pressures, k_{eff} is seen to increase further and this is due to the increase in solid conduction by the rearrangement of multilayer insulation wound around the Pulse Tube Cryocooler. The results for TSPTC1 plotted in FIGURE 4(b) are similar to that of SSPTC1. At lower pressures k_{eff} is found to be nearly constant, which points to the residual radiation heat transfer.

CONCLUSION

The performances of single and two-stage Pulse Tube cryocoolers have been studied in this work in the adverse conditions of loss of vacuum with and without thermal radiation shields. The experimental results of PTCs with and without thermal radiation shields under high vacuum provide the heat load due to radiation and the average emissivities of the cold and warm surfaces. Similarly, the experimental results on PTCs with thermal radiation shields under varying interspace gas pressures lead to effective thermal conductivities for gas conduction with respect to pressure. At higher interspace gas pressures, the heat load increases further due to increase in solid conduction by rearrangement of insulation layers.

The use of thermal radiation shields in high vacuum systems in general prevents sudden rise of temperatures and averts catastrophes. The same is also applicable in this case. Hence use of PTCs insulated with thermal radiation shields in high vacuum in the interspace serve to prevent sudden changes in the temperatures of systems that are being refrigerated by the Cryocooler.

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