Investigation of Two-Stage High Frequency Pulse Tube Cryocoolers

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ABSTRACT

In the past several years, we have investigated two-stage high frequency pulse tube coolers (PTC) for operation at 20 K to 40 K by simulation and experiment. Initially, a computer code, based on a thermal physics method, was developed to optimize the geometrical parameters of our first u-tube two-stage PTC, built and tested at the University of Giessen. In 2003, this PTC achieved the lowest temperature of 19.6 K with a 250 W electrical input, using a stainless steel mesh for the regenerator material. Here, we report on further tests conducted with this cooler. The experiments use lead spheres of different size or lead-plated mesh in the 2nd regenerator and then by use of a larger 2nd-stage pulse tube. There is no evident improvement in the cooling performance by the use of the lead materials. With the larger pulse tube, the refrigeration temperature has been reduced and the cooling capacity has been increased. A new version of this PTC with a coaxial configuration for the 1st stage was built at CAS Beijing. It resulted in a low temperature of 16.1K with 250 W electrical input power.

INTRODUCTION

Multistage high frequency (< 30-50 Hz) pulse tube coolers (PTC) are one of the latest developments in pulse tube research. The target is to provide cooling power at low temperatures such as 20 K, 10 K, or 4 K that cannot be reached by single-stage high-frequency PTC, or to provide cooling at two or more temperature levels, such as 150 K/80 K, 60 K/30 K, or 80 K/10 K/ 5 K.[1] Since 2002, several experimental results have been reported for two- or three-stage high frequency PTCs.[2-5]

Our first version of a two-stage high frequency PTC has a U-tube configuration for both stages. It reached a low temperature of 19.6 K with 250 W electrical input power at an operating frequency of 35 Hz.[6] This cooler that was built and tested at the University of Giessen, employed a stainless steel mesh for the regenerator material in both stages. For operation below 30 K, a better choice of regenerator material would be lead because of the higher volumetric specific heat as compared to stainless steel.

In the present paper, we report on tests of the above two-stage PTC by use of lead material as a regenerator matrix in the coldest part of the 2nd stage regenerator. Furthermore, we report on the cooling performance of a modified version of the PTC with an enlarged pulse tube diameter in the 2nd stage, and on the cooling performance of a new version with a coaxial configuration of the 1st stage that was built and tested at CAS Beijing.

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The lead materials were lead spheres with different size spheres or lead-plated stainless steel mesh that was supplied by the University of Jena.[7] Noticeable improvement in the cooling performance has been achieved by use of these materials.

Guided by numerical simulations[8, 9], the pulse tube diameter of the 2nd stage was increased, which further lowered the temperature and increased the cooling power. The new version with coaxial 1st stage and enlarged 2nd pulse tube achieves a lowest temperature of 16.1 K.

DESCRIPTION OF COOLERS AND TEST SETUP

Two versions of gas coupled two-stage PTC systems have been built, as shown in Figs. 1 and 2. Both PTCs are driven by a Leybold Polar SC7 linear compressor with a maximum input power of 250 W. As indicated in Fig. 1, both stages are equipped with inertance lines, buffer volumes and double-inlet flow resistance for phase adjustment. The original PTC (version 1) and the test setup has been described in more detail elsewhere.[6]

There are three differences between two coolers: Version 2, made at CAS, utilizes a coaxial arrangement of the 1st stage for compactness, and a radiation shield is employed to reduce 2nd stage radiation losses (Fig. 1). The cold tip of the second stage of version 2 is a cylindrical block (see Fig. 2), which makes it more useful for applications.

THEORETICAL ANALYSIS AND NUMERICAL SIMULATION

Four kinds of theoretical work have been conducted to investigate two-stage high frequency PTCs. The first is the numerical simulation to design the cooler based on a self-developed code.[8] The second one is a model based on the commercial SAGE software for verifying the test results and for finding further improvements.[9] The third one is the REGEN3.2 code[10] developed by NIST for optimization of the regenerator geometry and the matrix materials. The fourth is to use the commercial Fluent computational fluid dynamic (CFD) software to study the flow and heat transfer in the pulse tubes and the inertance tubes. The details of the theoretical work are not the subject of this paper, but some simulation results with SAGE are described below.

Figure 3 shows the typical results obtained by numerical modeling of the two-stage PTC with SAGE.[9] In the simulation, no double-inlet is used and a pV power of 150 W at the compressor outlet is assumed. Three different 2nd stage regenerative materials, i.e. stainless steel mesh, lead spheres, and hypothetical lead spheres with the heat conductance of stainless steel, have been simulated to try to achieve the possible lowest temperature.

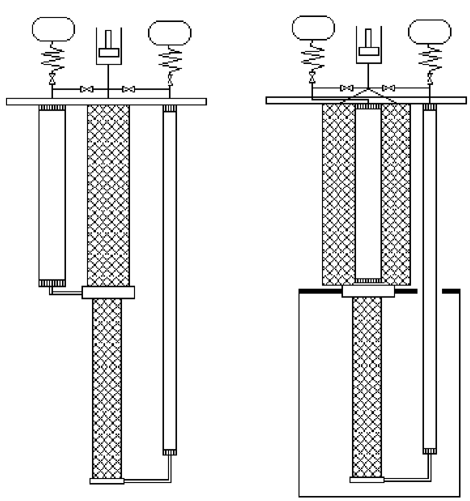

Figure 1. Sketch of the two stage pulse tube coolers; left: version 1, right: version 2.

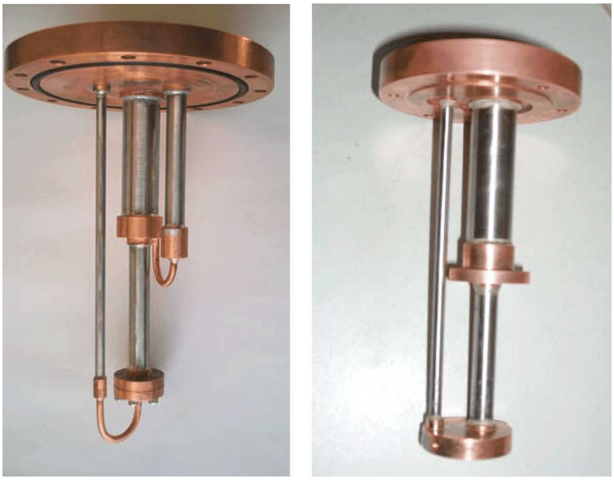

Figure 2. Photographs of the two-stage PTCs; left: version 1, right: version 2.

This is accomplished by calculating the cooling powers Q_{c1} and Q_{c2} of the 1st and 2nd stage for two fixed temperatures T_{c1} and T_{c2} at the 1st and 2nd stage cold tip, respectively. Assuming a linear variation of the load lines with temperature, the lowest temperatures are obtained at $Q_{c1} = 0$ or $Q_{c2} = 0$, as illustrated in Fig. 3. For stainless steel, lead spheres and lead spheres with low conductivity, the corresponding temperatures are $T_{c2} = 36.3$ K, 40.7 K, and 33.6 K, respectively (Fig. 3 a). Evidently, because of the high thermal conductivity of lead, the lead spheres yield the highest T_{c2} of 40.7 K. For the three kinds of regenerative material in the 2nd stage, the corresponding lowest temperatures of the 1st stage are 80.3 K, 71.4 K, and 71.7 K, respectively. The low flow resistance of the stainless steel mesh and the higher gas flow into the 2nd stage regenerator makes T_{c1} highest and reduces the slope of Q_{c1} versus T_{c1}, while the larger pressure drop in the bed of lead spheres lowers T_{c1} and increases Q.

TEST RESULTS AND DISCUSSION

Test of Lead Materials in Second Stage Regenerator

These tests were performed with the original version 1 of the PTC after replacing some portion of the stainless steel mesh (#500) in the coldest part of the 2nd regenerator by lead material, while the other parts of the PTC were kept unchanged. This could be done because there is a demountable flange at the 2nd stage cold tip, as seen from Fig. 2.

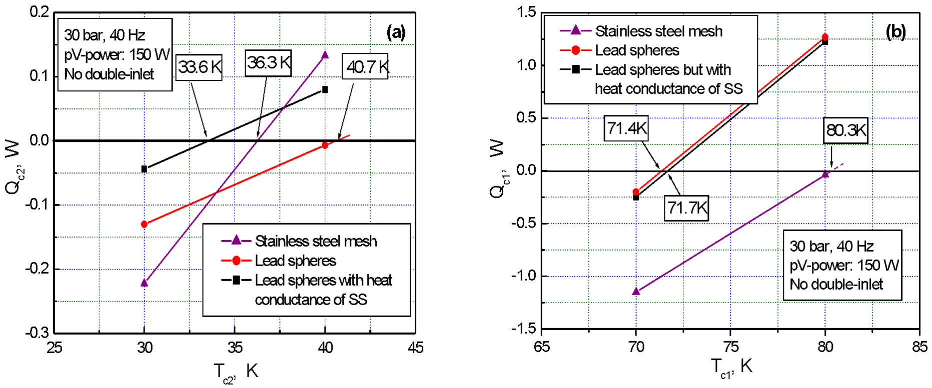

Figure 3. Cooling power versus temperature for (a) 2nd and (b) 1st stage of the PTC obtained by numerical simulation with SAGE.

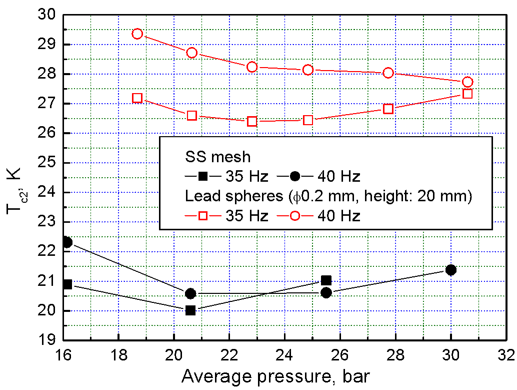

Figure 4. Lowest temperature of 2nd stage versus average pressure for stainless steel mesh and lead spheres at two different frequencies; compressor input power: 200 W; double-inlet opened.

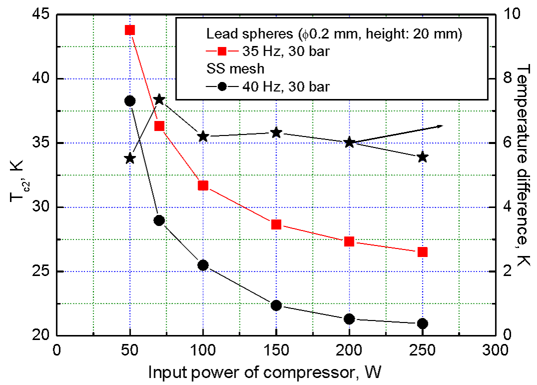

Figure 5. Lowest temperature of 2nd stage versus compressor input power for stainless steel mesh and lead spheres; the temperature difference is also plotted; double-inlet opened.

The first materials tested were three kinds of lead spheres with sphere diameters of 0.20, 0.15, and 0.07 mm that were packed with filling heights of either 10 or 20 mm.

Figs. 4 and 5 shows T_{c2} as function of average pressure or input power, respectively, with the 2nd regenerator filled with stainless steel mesh only or with a 20 mm high package of lead spheres (ϕ 0.2 mm). The tests were performed with the double-inlet opened.

Evidently, T_{c2} is 5-7 K higher with the lead spheres than with stainless steel mesh only, and this temperature difference is not much affected by average pressure and frequency (Fig. 4) or by input power (Fig. 5).

The comparison of different regenerator fillings in operation with double-inlet might be misleading because of the possibility of varying DC flow in the cooler. Therefore, the measurements of T_{c2} and T_{c1} as a function of input power for different regenerator fillings were also made with the double-inlet closed, as shown in Fig.6.

For lead spheres of different diameter, T_{c2} in Fig. 6 (a) is always higher than that with stainless steel mesh. The effect of sphere diameter on T_{c2} is very small, but a shorter packing height of 10 mm instead of 20 mm reduces T_{c2} by 2-3 K. This means that the longer the height of stainless steel mesh; the lower is the refrigeration temperature. This finding is consistent with the simulation results in Fig.3, where the higher T_{c2} of the regenerator with lead spheres is mainly attributed to the higher heat conductivity of lead. Another reason might be the relatively large sphere diameters and the small heat penetration depth at the operating frequency of 35-40 Hz, which is detrimental to the regenerative process. In addition, the smaller heat transfer area of spheres, as compared to mesh, will lead to an increased heat transfer loss.

Besides lead spheres, lead-plated stainless steel mesh (lead layer ≈ 8 μm, mesh no. 320), which was supplied by the University of Jena[7], has been tested. As shown in Fig. 6 (a), for this mesh with filling height

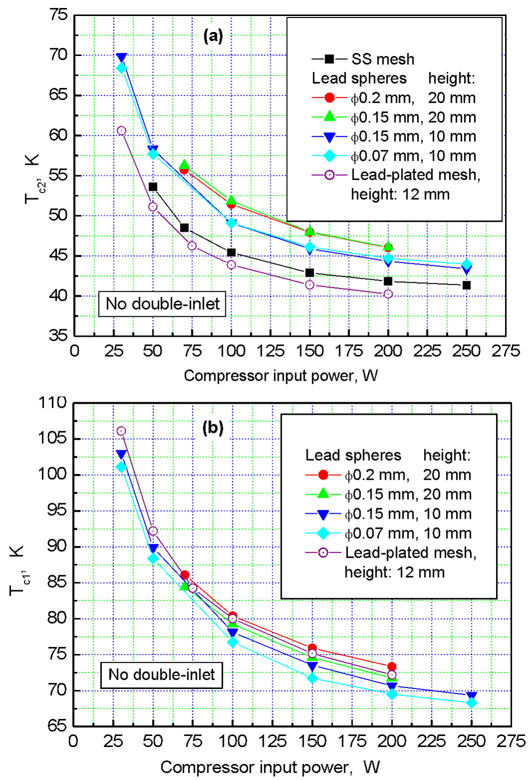

Figure 6. Refrigeration temperature as function of input power for different lead materials in 2nd regenerator; operation with double-inlet closed; (a) 2nd stage, (b) 1st stage.

of 12 mm, T_{c2} is lower than with stainless steel mesh by about 2 K. Because the inertance of the 2nd stage was also slightly changed, this does not mean that the lead-plated mesh is markedly better, but it shows similar performance as stainless steel mesh.

Corresponding to Fig.6a, Fig.6b shows the variation of T_{c1} with input power for the different regenerator fillings. For the lead spheres with smallest diameter of 0.07 mm, T_{c1} is lower than that in the other cases because the flow resistance of this bed of lead spheres is evidently higher, and more gas flows into the 1st stage, which is also seen from measurements of the pressure wave amplitude. In contrast, for the 0.2 mm lead spheres and for the lead-plated mesh, the flow resistance is comparatively low, so that more gas is consumed by the 2nd stage. Consequently, the 1st stage temperature is relatively high in the two latter cases. The results in Fig. 6 demonstrate how the gas distribution among the stages affects the refrigeration temperatures of a PTC.

In Fig.6a, T_{c2} for the lead-plated mesh without double-inlet is lowest with 40 K at 200 W input. However, with double-inlet opened, the 2nd stage refrigeration temperatures with stainless steel and with lead-plated mesh are nearly the same at input powers above 100 W, corresponding to T_{c2} below 25 K, as illustrated in Fig. 7. This means that the higher heat capacity of the lead-plated mesh does not yield the desired reduction in T_{c2} near 20 K.

From Fig. 8, the cooling power for the two different mesh types is nearly the same.

Effect of Second Stage Pulse Tube Dimension

As predicted by modeling with SAGE, a 2nd stage pulse tube with a larger volume should give better cooling performance. Based on this finding, the 2nd stage pulse tube of the PTC (version 1 in Fig. 2) was replaced by a tube with a 60% larger cross sectional area. In the test of this modified PTC, the lead-plated mesh was left in the 2nd stage regenerator.

Fig. 9 compares the variation of refrigeration temperatures T_{c1} and T_{c2} as function of input power for the original small and the new large 2nd stage pulse tube at operation without double-inlet. For the larger

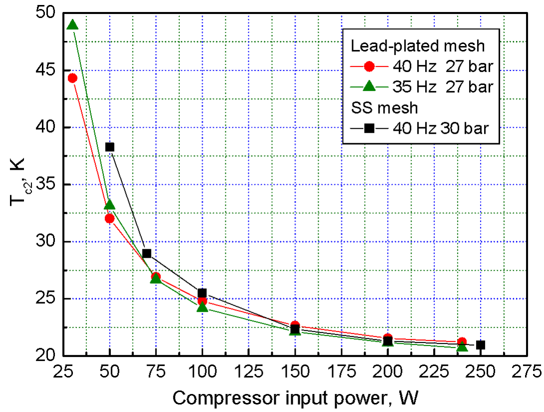

Figure 7. T_{c2} versus input power for stainless steel and lead-plated mesh; double-inlet opened.

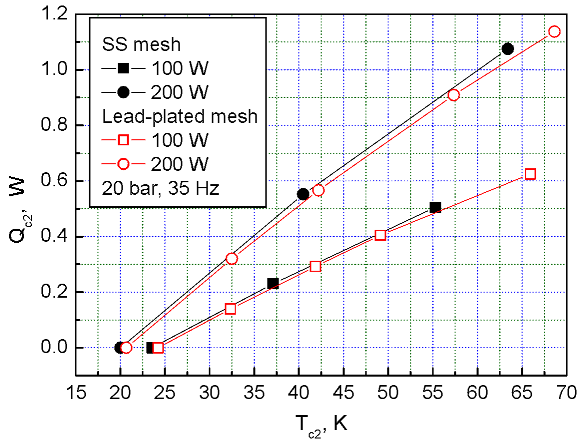

Figure 8. Cooling power versus T_{c2} for stainless steel and lead-plated mesh; double-inlet opened.

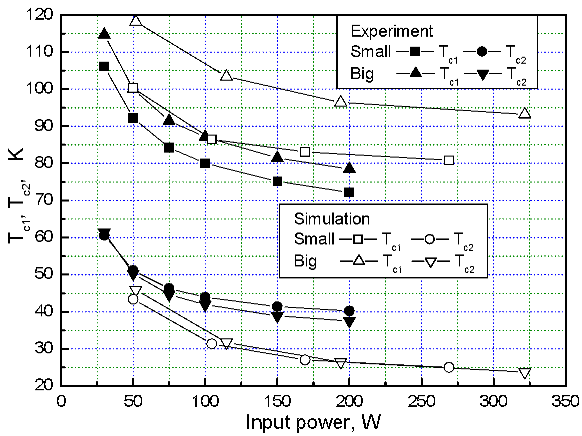

Figure 9. Temperatures versus input power for small and large diameter 2[nd] stage pulse tube; without double-inlet.

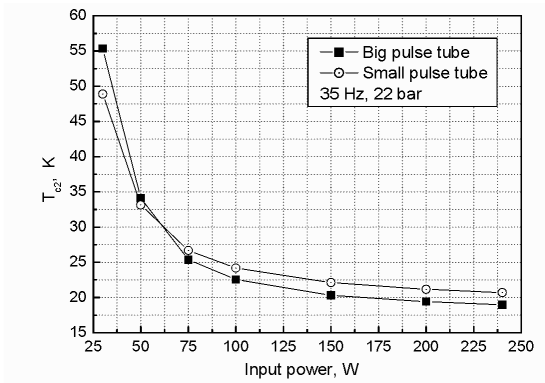

Figure 10. 2nd stage temperature versus input power for small and large diameter of 2nd stage pulse tube; operation with double-inlet.

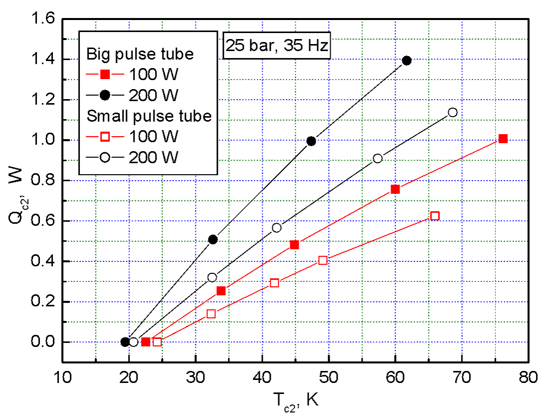

Figure 11. 2nd stage cooling power versus temperature for small and large diameter of the 2nd stage pulse tube; operation with double-inlet

pulse tube, T_{c2} is 1-3 K lower than the smaller one. Correspondingly, because more gas flows into the larger 2nd stage pulse tube, the temperature of the 1st stage cold tip is about 5-8 K higher than before.

Also shown in Fig. 9 are the results of numerical simulations based on a self-made program.[8] The numerical results reflect the tendency in the experimental data for the calculated T_{c2} to be lower than in the experiments. Meanwhile, the calculated T_{c1} is evidently higher than the experimental value. Presumably in the simulation, the 2nd regenerator loss is underestimated at the lower temperatures.

For operation with the double-inlet opened, Fig. 10 shows the variation of T_{c2} with input power for the two different pulse tubes. With the big pulse tube, T_{c2} is 1-2 K lower than with the small one at input powers above 75 W. The more remarkable effect of increased pulse tube diameter is seen from the comparison of the cooling power in Fig. 11.

With the big pulse tube, the slope of the load line is markedly increased. At 200 W input, a cooling power of 0.4 W at 30 K is obtained with the big pulse tube, as compared to 0.25 W at 30 K with the original smaller tube.

The cooling load map for the PTC with big 2nd pulse tube is displayed in Fig. 12. The data is measured with an electric input power of 200 W and average pressure of 24 bar.

Performance of PTC Version 2 with Coaxial First Stage

As mentioned before, a new version of this two-stage PTC with a bigger 2nd pulse tube and coaxial first stage (version 2 in Fig. 2) has been fabricated and tested at CAS.

Fig. 13 compares the variation of T_{c2} of the two PTC versions with the compressor input power. The 2nd stage temperature of cooler, version 2, is 3-4 K lower than that of version 1 for input powers above

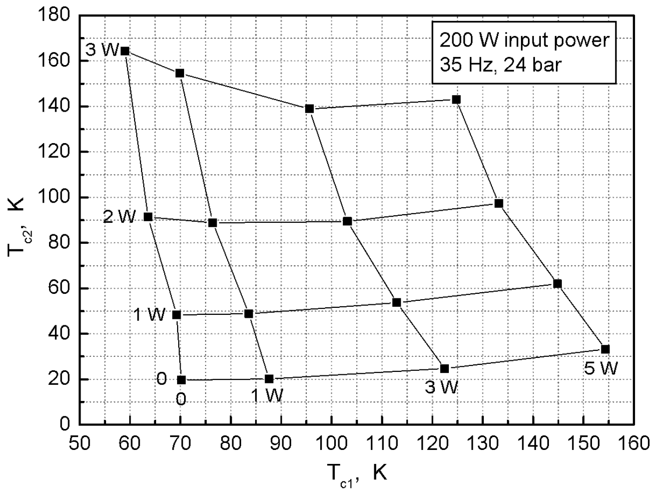

Figure 12. Cooling load map of PTC version 1 with large 2nd stage pulse tube; with double-inlet.

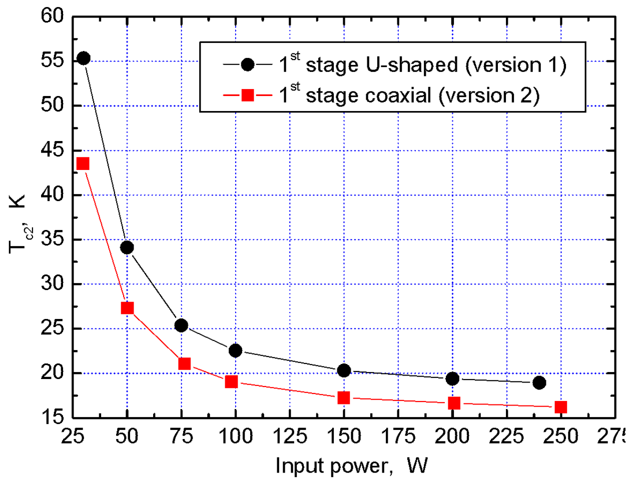

Figure 13. T_{c2} versus input power for the two PTC versions (big 2nd pulse tube).

75 W. With version 2, a low temperature of 16.1 K is achieved at 250 W input, as compared to 18.96 K at 240 W input with version 1. One important reason for this improvement is the radiation shield that is cooled by the 1st stage of PTC version 2 (see Fig. 1), whereas with version 1, only multilayer insulation was used.

With regard to the cooling power shown in Fig. 14, the slopes of the load lines of version 2 are somewhat lower, which results in an intersection of the load lines of version 1 and 2 at 33-34 K. The reason for the slightly reduced slopes with version 2 could be attribute to the small change of dimensions.

CONCLUSIONS

Two versions of a two-stage high frequency PTC have been investigated, with the aim to lower the refrigeration temperature of the 2nd stage. Tests of different packages of lead spheres in the coldest part of the regenerator showed an increase of base temperature, while with the lead-plated mesh the cooling performance is similar to that with stainless steel mesh only. Both simulation and experiment show an improvement of cooling performance by enlarging the volume of the 2nd stage pulse tube. The latest version of this PTC with coaxial 1st stage, built at CAS, achieved a base temperature of 16.1 K.

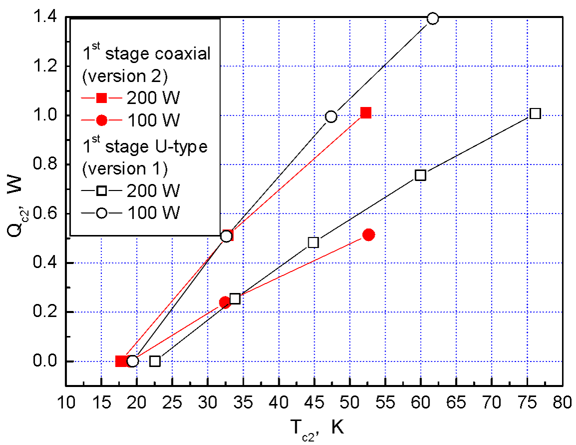

Figure 14. Cooling power of 2nd stage versus T_{c2} for the two PTC versions (big 2nd pulse tube) at input powers of 100 and 200 W; operation with double-inlet.

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