Performance of a Pulse Tube Cryocooler with Two Separate Stages using ^3He in the Second Stage

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In this paper, the performance of a two-stage pulse tube cryocooler with ^3He as the 2nd stage working fluid is presented. A minimum no-load temperature of 1.27 K at the 2nd stage with the 1st stage at 23 K has been achieved. At an input power of 1.49 kW to the 2nd stage, the cooler provides a maximum cooling power of 735 mW at 4.2 K with ^3He.

INTRODUCTION

The development in phase shifting methods and the utilization of magnetic regenerative materials have led to great progress in pulse tube refrigeration. So far, the lowest no-load temperature of 2.07 K was obtained with ^4He by means of a liquid nitrogen precooled two-stage pulse tube cryocooler (PTC) [1].

For regenerative cryocoolers using ^4He as the working fluid, a refrigeration temperature limit of 2K or so is induced by the λ superfluid phase transition of ^4He. The sharp increase of the fluid specific heat accompanying the superfluid phase transition makes regenerators disabled. Besides, the thermal expansion coefficient of ^4He also equals zero near 2 K, which means that adiabatic compression or expansion occurs without change in temperature, and therefore no refrigeration will be produced by the pulse tube cooler. Different research groups [2-4] succeeded to break the temperature barrier of ^4He by using ^3He, whose superfluid phase transition occurs in the Millikelvin temperature region and whose thermal expansion coefficient approaches zero close to 1 K (see [2, 4] for more details).

By a three-stage pulse tube cryocooler, a minimum no-load temperature of 1.78 K with ^3He was achieved by the Eindhoven group [2]. A minimum no-load temperature of 1.47 K with ^3He was obtained by a two-stage GM cooler employing a novel rare earth regenerator material [3].

Recently, in our research group a lowest temperature of 1.27 K has been achieved by means of a newly designed PTC [4]. This cooler consists of two pulse tube stages with separate gas supply. To save the amount of ^3He, only the smaller second stage is charged with ^3He, while the first stage still operates with ^4He as working fluid. Here we present new results on the cooling performance of this PTC including cooling load maps with ^3He as working fluid.

EXPERIMENTAL SET-UP

A schematic of the two-stage PTC is shown in Fig. 1. The cooler consists of two parallel separate pulse tube stages. The incoming gas to the second stage is precooled by a heat exchanger thermally connected to the cold end of the first stage. Compared to that of coolers with common gas supply, such design presents higher flexibility in distribution of cooling capacity of the stages and allows an easier adjustment of dc-flow. In addition, this arrangement makes possible to operate the two stages with different compressors and at different operating frequencies.

The matrix of the coldest part of the second stage regenerator consists of layers of Pb, ErNi and $HoCu_2$ spheres, as indicated in Fig. 1. Two commercial helium compressors, Leybold CP4000 (or CP6000) and RW2, are employed for driving the first and second stage, respectively. A more detailed description of the cooler has been given previously [4].

The temperatures of the 1st and 2nd stage cold platforms are measured by means of calibrated platinum and Cernox resistance thermometers, respectively. Net cooling powers of the 1st and 2nd stage are measured using resistive heaters attached to the cold platforms. Dynamic pressures are recorded by piezoelectric pressure sensors connected to the inlet of each stage regenerator.

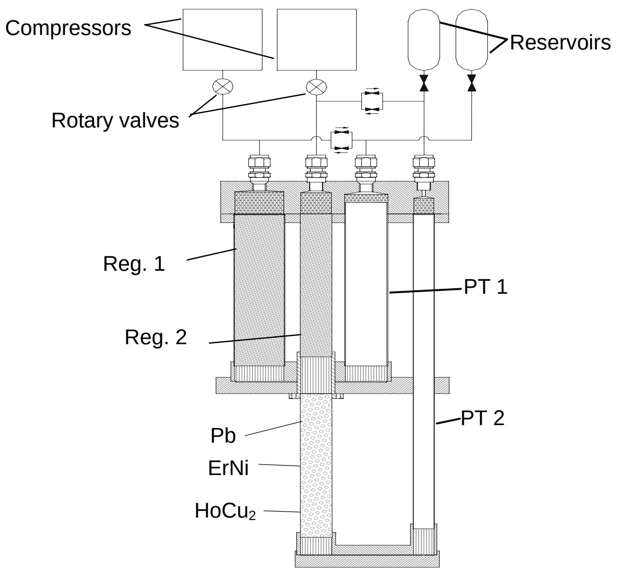

Figure 1 Schematic of the two-stage pulse tube cooler with separate stages.

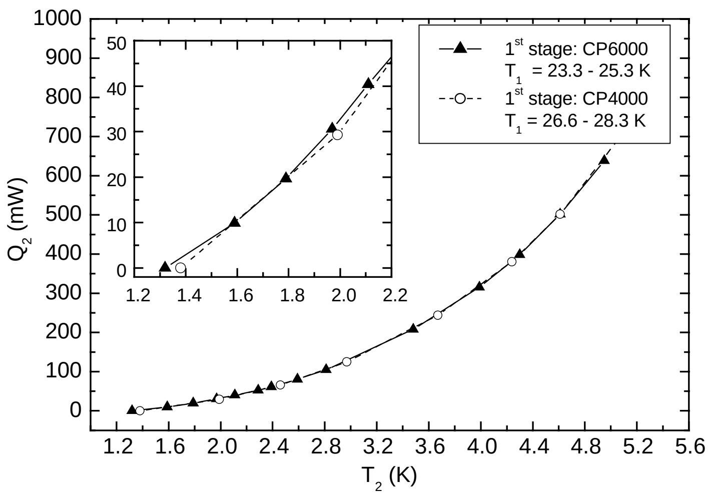

Figure 2 2nd stage cooling power versus temperature with the 1st stage driven by CP6000 or CP4000.

EXPERIMENTAL RESULTS

All of the cooler tests are performed with the 1st stage charged with ^4He to an (absolute) pressure of 17.5 bar at ambient temperature. The 2nd stage is operated with ^3He at a charging pressure of 17.0 bar, if not stated otherwise. The rotary valve timings (expansion to compression interval in a cycle) for both stages are fixed. In the following Q_1, T_1 and Q_2, T_2 denote the net cooling power and temperature of the 1st and 2nd stage, respectively.

Fig. 2 displays the net cooling power of the 2nd stage as a function of temperature either with the 1st stage driven by the CP4000 or CP6000 compressor. The operating parameters for both cases are optimised without additional heat load on both stages ($Q_1 = Q_2 = 0$). The 1st stage temperature is around 24 K with CP6000 (input power: 6.1 kW) and around 27 K with CP4000 (input power: 4.3 kW). The load curves in Fig. 2 are almost superposed, which indicates that the performance of the 2nd stage is not sensitive to 1st stage temperature except at temperatures well below 2 K (see inset to Fig. 2). With CP6000 operation of the 1st stage, the 2nd stage minimum no-load temperature is 1.32 K, which is 0.06 K lower than that with CP4000 (T_2 = 1.38 K).

With CP6000 on the 1st stage, the cooler provides 33 mW, 134 mW and 371 mW at 2.0 K, 3.0 K and 4.2 K, respectively. With CP4000, the cooling power at 2.0 K is slightly reduced to 30 mW at 2.0 K, while at higher temperatures it is essentially the same as with CP6000. The electrical power consumption by the 2nd stage (RW2 compressor) is about 1.3 kW.

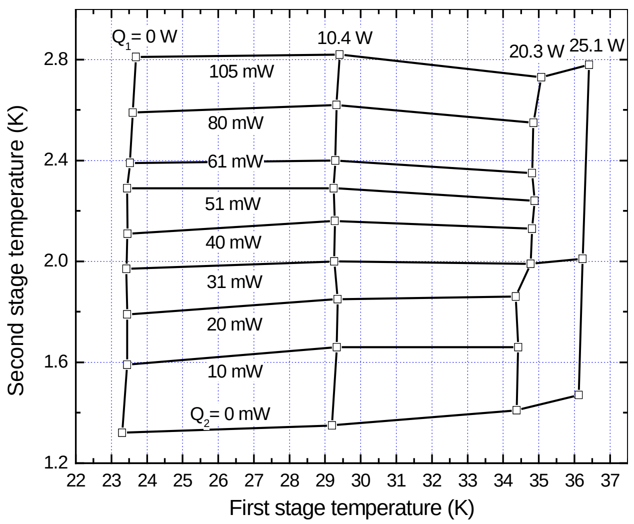

Figure 3 Cooling load map below 3 K; CP6000 compressor on 1st stage; parameters optimised for minimum temperature at $Q_1 = Q_2 = 0$.

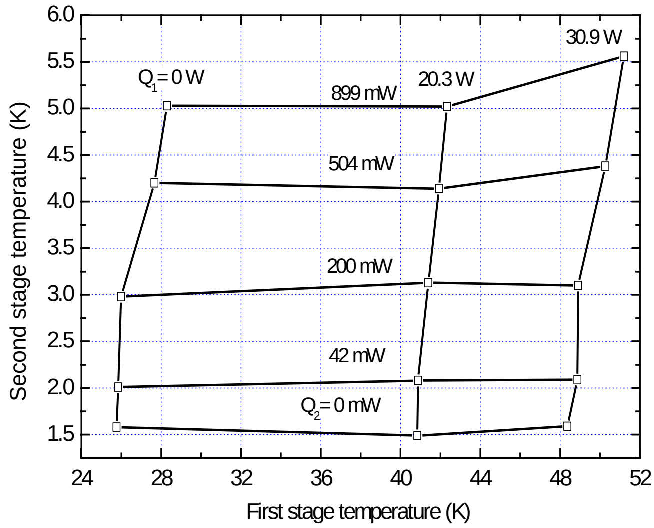

Figure 4 Cooling load map with the 1st stage operated on the CP4000 compressor; parameters optimised at $Q_1 = 0$ and $Q_2 = 50$ mW.

A more detailed behaviour of the cooling performance with load on both stages and with the 2nd stage operating below 3 K can be seen from the cooling load map in Fig. 3. The data were obtained with CP6000 on the 1st stage after optimising the cooler for minimum temperature without load on both stages. It follows from Fig. 3 that the 2nd stage temperature at fixed cooling power depends only slightly on the 1st stage temperature and thus on Q_1. For example, at $Q_2 = 31$ mW the 2nd stage temperature is 1.97 K at $T_1 = 23.4$ K ($Q_1 = 0$) and rises to 2.01 K at $T_1 = 36.2$ K ($Q_1 = 25.1$ W). The measured input powers to the CP6000 and RW2 compressor in Fig. 3 are 6.11 - 6.36 kW and 1.26 - 1.36 kW, respectively, depending on the heat load on each stage.

Higher 2nd stage cooling powers above ≈ 1.8 K are achieved by optimising the cooler under an applied heat load ($Q_2 > 0$) at the cost of an increased no-load temperature. Fig. 4 shows a cooling load map that was measured after optimisation at $Q_1 = 0$ and $Q_2 = 50$ mW. In these tests the 1st stage was operated on the CP4000 compressor. The minimum no-load temperature ($Q_2 = 0$) is now 1.58 K, 1.49 K, and 1.59 K for 1st stage cooling powers of $Q_1 = 0$, 20 W, and 31 W, respectively. The 2nd stage provides cooling powers of 42 mW, 38 mW and 34 mW at 2.0 K, as well as 518 mW, 528 mW and 464 mW at 4.2 K with $Q_1 = 0$, 20 W and 31 W, respectively.

The thermal expansion coefficient of ^{3}He approaches zero at lower temperatures when the pressure decreases [2, 4]. So does the temperature limit of a pulse tube cooler with ^{3}He working fluid. Therefore the cooling performance of the 2nd stage has also been tested under different ^{3}He working pressures. Fig. 5 displays the cooling power of the 2nd stage for three average working pressures of $\langle p \rangle = 9.2$ bar, 10.2 bar, and 12.4 bar, where $\langle p \rangle = 10.2$ bar corresponds to the standard ^{3}He charging pressure of 17.0 bar. In the tests in Fig. 5 the 1st stage was driven by the CP6000 compressor. The cooling performances under the three average working pressures are very close together. The solid curve in Fig. 5 for $\langle p \rangle = 10.2$ bar, which gives a minimum temperature of 1.32 K, corresponds to the load curve with CP6000 in Fig. 2. A lower no-load temperature of 1.27 K is obtained by decreasing the ^{3}He average working pressure to 9.2 bar. At this low working pressure, the electric power consumption of the 2nd stage is only 1.17 kW.

Fig. 6 gives the cooling load map with increased ^{3}He average working pressure of 12.4 bar and with the cooler optimised under a high heat load to the 2nd stage ($Q_1 = 0$, $Q_2 = 545$ mW). The minimum temperature of the 2nd stage is now 1.47 K with $T_1 = 35.5$ K at $Q_1 = 20.3$ W. A cooling power of 735 mW at 4.2 K is obtained with $T_1 = 24.6$ K at $Q_1 = 0$.

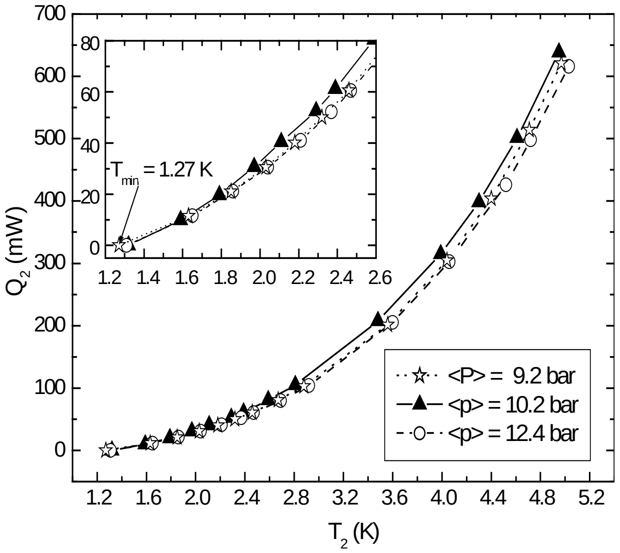

Figure 5 Cooling power of the 2nd stage operated at different ^{3}He working pressures; 1st stage driven by CP6000; Q_1 = 0, T_1 = 23 – 26 K; parameters optimized for minimum temperature at $Q_1 = Q_2 = 0$.

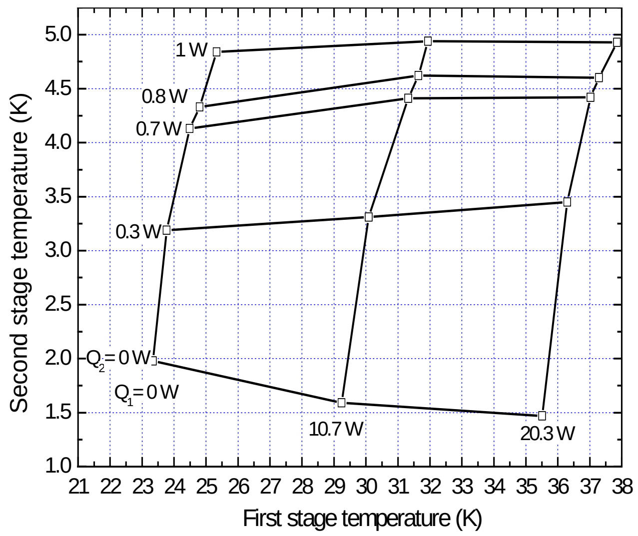

Figure 6 Cooling load map at an increased ^{3}He average pressure of <p> = 12.4 bar; CP6000 compressor on 1st stage; parameters optimized for minimum temperature at Q_1 = 0 and Q_2 = 545 mW.

SUMMARY

A minimum no-load temperature of 1.27 K with ^{3}He in the 2nd stage is achieved by the present two-stage PTC, which is the lowest temperature obtained by regenerative cryocoolers up to now. The cooler can provide 42 mW at 2.0 K with 1.3 kW input power to the 2nd stage and 4.3 kW to the 1st stage. After optimization at Q_1 = 0 and Q_2 = 545 mW, the maximum cooling power at 4.2 K is 735 mW with an input power of 1.49 kW to the 2nd stage at a 1st stage temperature of 24.6 K and a 1st stage input power of 6.2 kW.

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