

Investigation of a Thermally Coupled Two-Stage Stirling-Type Pulse Tube Cryocooler

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ABSTRACT

Multi-stage Stirling-type pulse tube cryocoolers driven at high frequency (30-50 Hz) have been an important research focus in recent years. A two-stage Stirling-type pulse tube cryocooler with thermally-coupled stages was designed and characterized two years ago, and some results have been published. To study the effect of first-stage precooling temperature, some additional performance characteristics have been experimentally investigated. They show that for high input power, when the precooling temperature is lower than 110 K, the effect of first-stage temperature on the second stage temperature is quite small. Also seen is the effect of precooling temperature on the pulse tube temperature distribution; this is the first time that the author has noticed this phenomenon. The effect of mean working pressure on lowest refrigeration temperature was also investigated. Our lowest temperature of 12.8 K with 500 W of input power was achieved using an average pressure of 1.2 MPa; this shows the benefit of low average pressure.

INTRODUCTION

Multi-stage pulse tube cryocoolers (PTCs) that are capable of achieving lower cooling temperatures and which meet the cooling requirements at different temperature levels have been researched and developed since the invention of the pulse tube cooling concept.

In recent years, multi-stage Stirling-type PTCs with high operating frequencies (30-50 Hz) have been investigated [1-5]. Chan et al. successfully developed a thermally coupled two-stage PTC that can simultaneously provide cooling powers of 2.25 W at 35 K and 17.4 W at 85 K [1]. Nast et al. achieved a lowest temperature of 19.8 K for a 35 K application [2]. The two-stage PTC of Nguyen et al. realized 1.4 W of cooling power at 18.3 K, simultaneously with 6 W of cooling power at 67 K [3]. Recent development of pulse tube coolers have shown that four-stage high-frequency PTCs have achieved a lowest temperature of 3.8 K with ³He as the working gas, corresponding to 4.3 K with ⁴He [4, 5]. The NGST team has achieved a lowest temperature of 6.5 K for their high-efficiency three-stage pulse tube cooler [6].

The author started to investigate two-stage pulse tube coolers in 2003. At the very beginning, a cooling temperature of 19.6 K was attained with a two-stage PTC version [7]. And, later this cooler was modified in China and reached the lowest temperature of 16.1 K [8, 9]. In

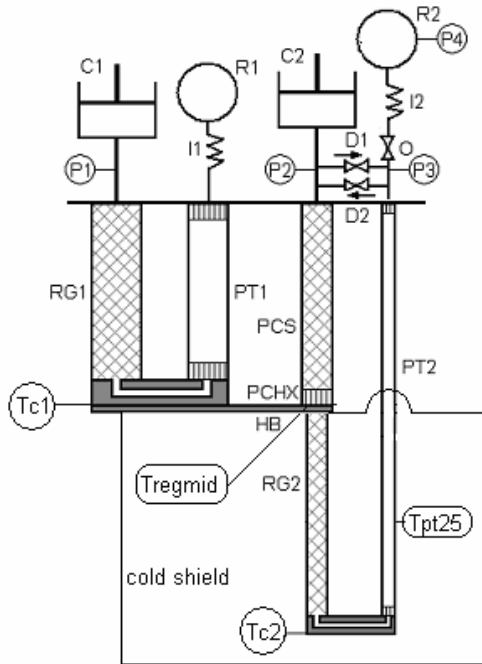


Figure 1. Schematic of thermally-coupled two-stage Stirling-type PTC. C1: first stage compressor, RG1: first stage regenerator, Tc1: first stage cold tip, PT1: first stage pulse tube, I1: first stage inertia tube, R1: first stage reservoir, C2: second stage compressor, PCS: precooling section of second stage regenerator, PCHX: precooling heat exchanger of second stage regenerator, HB: heat bridge, RG2: second stage regenerator, Tc2: second stage cold tip, PT2: second stage pulse tube, O: orifice valve, I2: second stage inertia tube, R2: second stage reservoir, Tregmid: precooling temperature of middle of regenerator, Tpt25: wall temperature at second stage pulse tube of 1/4 position, D1 and D2: double-inlet valves of second stage cooler

2004, the present two stage system was set up, and the performance was investigated carefully; at that time the experiment was mainly conducted by Tang Ke. Some results have been published [10]. Reported here is further study of the cooler to investigate first-stage effects.

EXPERIMENTAL APPARATUS

Figure 1 is a schematic of the thermally-coupled two-stage Stirling-type PTC with a U-shaped configuration for both stages. The pulse tubes are arranged in parallel, with the warm ends and the phase shifters at ambient temperature. The first stage operates with inertia tube and reservoir. For the second stage, an orifice and second-inlet are used for phase shifting in addition to the inertia tube and reservoir. For control of the DC flow, the double-inlet consists of two custom-made needle valves in an anti-parallel arrangement. A copper tube for water cooling is wrapped and soldered around the hot end of each cooler stage.

The two-stage coolers are driven separately by two linear compressors (Leybold Polar SC7) with input powers of 0-250 W each. A heat bridge is employed for the thermal connection of the cold tip of the first stage cooler and the precooling heat exchanger of the second stage regenerator. The heat bridge is composed of two copper plates connected by copper braid. A copper radiation shield, which is thermally attached to the first stage cold tip, surrounds the low temperature part of the second stage. In addition, aluminized Mylar foil is wrapped around the two stages and the copper shield to reduce radiation losses.

The pulse tube used for the first stage has a diameter of 12 mm and a length of 65mm, while the pulse tube for the second stage has a diameter of 7 mm and a length of 165mm. The regenerator matrix consists of 400-mesh stainless steel screens for the first-stage regenerator and the precooling section of the second-stage regenerator. The coldest part of the second-stage regenerator uses 500-mesh screens. Helium is used as working fluid for both stages.

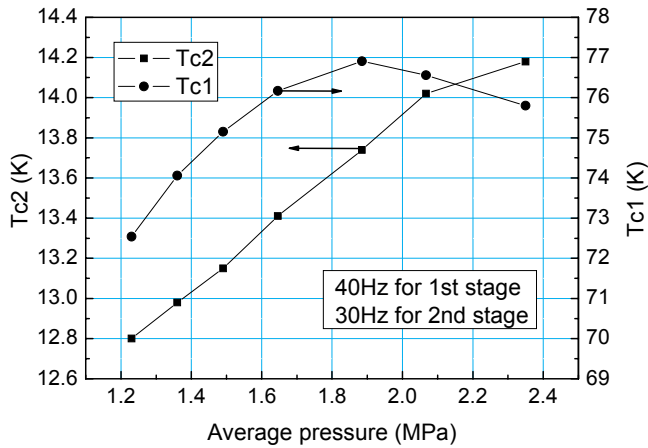


Figure 2. Effect of second-stage mean fill pressure on first and second-stage temperature. Both stages are running with 250W input power. First stage runs at 40Hz and 2.7MPa average pressure, while second stage at 30Hz operating frequency.

The temperatures at the first- and the second-stage cold tips are measured by calibrated platinum (PT100) and Cernox resistance thermometers, respectively. The cooling powers of the two stages of the cooler are measured by two resistive heaters attached to the cold tips.

EXPERIMENTAL RESULTS AND ANALYSIS

The main purpose of this investigation was to study the effect of precooling temperature on second-stage temperature. The first stage is used to provide cooling power to the precooling heat exchanger and the radiation shield; it is an important parameter in the design of a two-stage or multi-stage cooler. Based on previous optimized experimental results, the operating frequency and the charge pressure of the first stage were fixed at 40 Hz and 2.7 MPa. For the second stage, the settings of the orifice and second-inlet valves were optimized and essentially fixed, and then the mean working pressure was changed and studied. The study of the effect of precooling temperature on second-stage temperature was also based on the optimized valve settings.

Effects of Mean Working Pressure on No-load Cooling Temperature

At the very beginning of work with this cooler, a main objective was to achieve the lowest temperature [11, 12] through the optimization of different parameters. Varying the drive frequency indicated that a lower frequency such as 30Hz achieved the lowest temperature. Different fill pressures were also explored, and a low average pressure such as 2.2 MPa was found to be better. After optimization, a no-load temperature of 12.96 K was achieved with 200 W input power at 30 Hz applied to the second stage with 2.2 MPa fill pressure, while the first stage was driven with 200 W input at 40 Hz and 3.0 MPa fill pressure.

After the above-mentioned experiments, different tests were performed, and the system was changed only slightly from its past configuration. However, in this state it was not possible to reproduce the above-mentioned lowest temperature. In an attempt to recover the previous performance, fill pressure was further lowered to reveal its effect. Thanks to the large swept volume of the compressor, the input power was able to be increased to 250 W for both stages without over-stroking during the test. Shown in Fig. 2 are typical results. At 2.2 MPa, the lowest temperature is at around 14.1 K; this is about 1.1 K higher than that of the past lowest

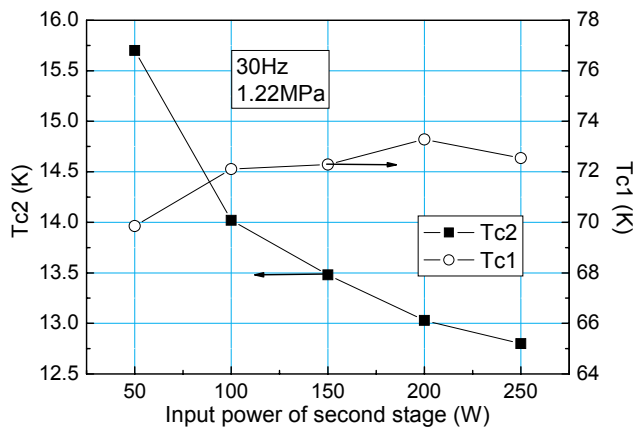


Figure 3. Effect of second stage input power on second stage lowest temperature while first stage is kept at around 70 K.

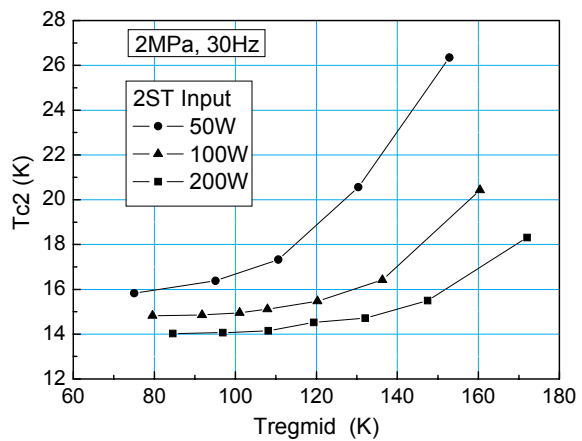


Figure 4. Relation of firststage precooling temperature Tregmid vs. Tc2 for three typical input power.

temperature. As shown in Fig.2, the temperature Tc2 drops almost linearly with fill pressure. For the lowest fill pressure of about 1.22 MPa, the lowest temperature of 12.80 K was achieved. According to this result, if past 12.96 K could be reproduced, an even lower temperature below 12 K should be achievable with this PTC. Also shown in the figure is the first-stage refrigeration temperature, Tc1. The fluctuation of Tc1 reflects mainly the load change of precooling the second stage; for sure it also reflects the load impact of DC flow. This phenomenon is evident during the valve setting and control process, and this will be discussed further later.

Shown in Fig. 3 is the relation between second-stage input power and Tc2, while Tc1 is keep at around 70K by controlling the first-stage input power. For powers over 100 W, increasing input power has a diminishing effect in lowering Tc2, though one can still get even lower temperatures by using higher input power levels.

Effect of Precooling Temperature on Refrigeration Temperature

Here, the effect of precooling temperature was our focus, and we fixed the fill pressure at 2 MPa and the frequency at 30 Hz. The relation between Tregmid (second stage regenerator middle temperature, one end of first stage heat bridge) and Tc2 was then studied by changing the

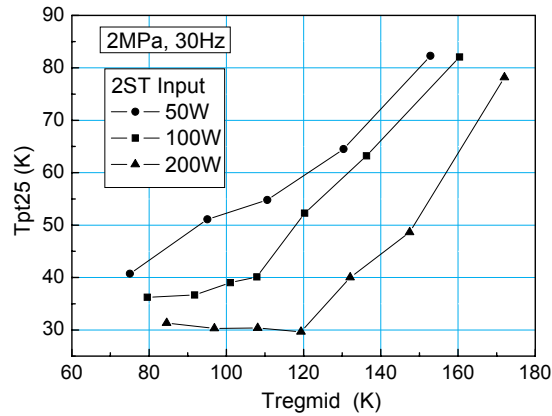


Figure 5. The change of pulse tube wall temperature Treg25 vs. precooling temperature Tregmid corresponding to Fig.4.

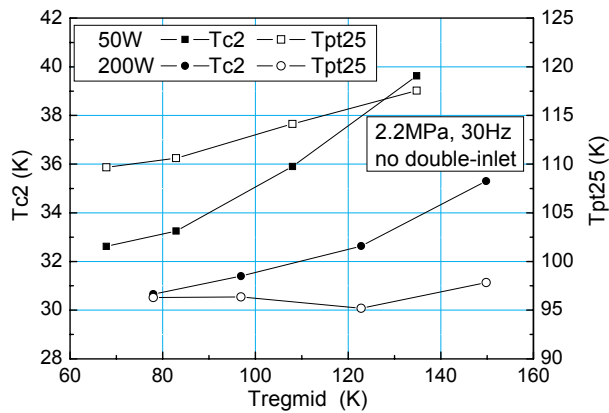


Figure 6. Change of temperature Tc2 and Tpt25 vs. Tregmid for the case of no double-inlet and two different input powers.

first-stage input power. For three input powers to the second stage (50 W, 100 W and 200 W) the relation between the two temperatures is shown in Fig. 4. For 100 W and 200 W input power, until Tregmid increases to 120 K, the effect of the precooling temperature on Tc2 is within 1 K, while for 50 W input power, the temperature Tc2 begins to go up quickly.

For a fixed input power to the second stage, with Tregmid increasing, the pressure wave in the pulse tube will also increase a little, but normally this will not greatly affect the temperature distribution in the pulse tube, and generally a higher pressure wave decreases Tpt25. But, for the present cases, with Tregmid increasing, Tpt25 increases also, as shown in Fig. 5. First, one may pay attention to the unsmooth temperature distribution. Though we tried to avoid this effect, it was caused by adjusting the double-inlet valve to minimize DC flow and its effects on the temperature distribution. For comparison, shown in Fig. 6, is the relation of Tc2 and Tpt25 vs. Tregmid without the double-inlet. Without the double-inlet, the variation of Tc2 is similar to that of Fig. 4, both for the amplitude of several Kelvin and the tendency to gradually increase. For 200 W input, Tpt25 changes only about 5 K, while for 50 W, it is limited to 10 K; this corresponds to the double-inlet case of about 50 K for 200 W and 40 K for 50 W input. There are several explanations: one is due to the actual gas effect. For temperatures higher than 30 K, helium is more like an ideal gas, and this results in the typical distribution of Fig.6. With the

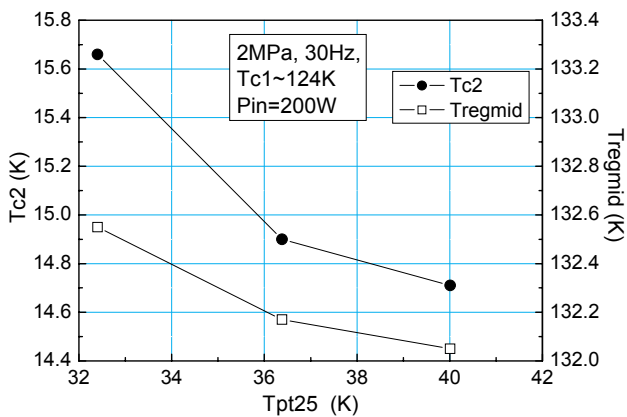


Figure 7 A typical result of Tc2 and Tregmid vs. pulse tube wall temperature Tpt25.

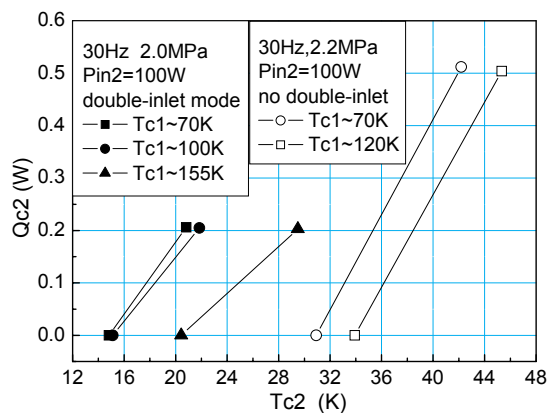


Figure 8. Cooling load curves for five different Tc1 temperature at 100W input power.

double-inlet open, Tc2 goes down to below 20 K, non-ideal gas effects dominate the temperature distribution, and Tpt25 goes down quickly; this is what is shown in Fig. 4 when Tregmid is low. When Tregmid goes up and Tc2 also goes up, the distribution will come back to the case of Fig. 6. This could be part of the reason, but not enough, because Tc2 is still quite low when Tpt25 begins to rise. Another possible reason is that the pulse tube distribution is not just determined by gas properties and gas flow, but also by the efficiency of the regenerator heat transfer. This means the heat transfer temperature difference of the regenerator may have an effect on the pulse tube temperature distribution. This needs further investigation. A third reason may be attributes to the phase controlling effect of the double-inlet, but not its DC flow effect. The double-inlet is really important here, as it greatly increases the pressure wave in the pulse tube. In this case, typically the pressure wave amplitude in the pulse tube is 1.5 times higher than without the double-inlet. These explanations need further study and confirmation; they will be the subject of future work.

As introduced before, DC flow control is important and must be addressed. To reveal this, a typical result is shown in Fig. 7. If Tpt25 is slowly increased in temperature by adjusting the double-inlet valve, then Tc2 decreases about 0.9 K, and Tc1 and Tmidreg decrease also, which

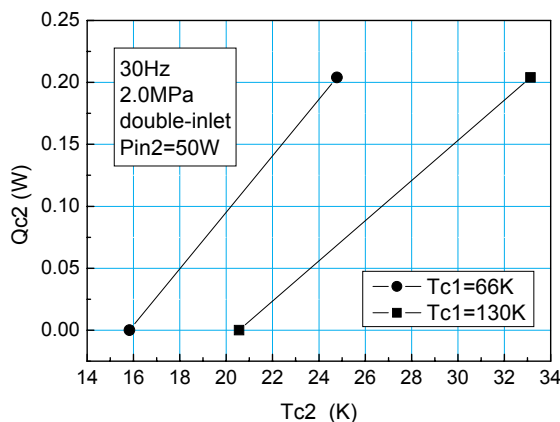


Figure 9. Cooling load curves for two different T_{c1} temperatures with 50W input power.

means that the precooling is decreased also by about 0.4 K. This shows the complex test process and the need to carefully check the data.

Effect of Precooling Temperature on Refrigeration Capacity

In the previous section, it was shown that the temperature T_{pt25} increases at high precooling temperatures. The cooling power was also measured to check the variation, as shown in Figs. 8 and 9. From Fig. 8, for 100 W input power in the double-inlet mode, the slope varies little for changes in T_{c1} from 70 K to 100 K. When T_{c1} is increased to 155 K, the slope becomes less. This is the same for 50 W input power as shown in Fig. 9. In Fig. 8, two curves for the no-double-inlet case are also shown. For this case, even though T_{c2} changes, the slope remains almost constant. Not shown here is that, without the double-inlet, a big Tregmid variation doesn't produce a big variation in T_{pt25} . The slope change with the double-inlet could be attributed to the change of regenerator loss, but I am wondering if this is related to the high pulse tube temperature T_{pt25} .

Simulated Effect of Precooling Temperature

For the above-mentioned results, a simulation was carried out for comparison. This simulation was based on an improved version of the PT from a former program [13]; it has been used for the present cooler design.

Shown in Fig. 10 are typical results of refrigeration temperature vs. precooling temperature, and Fig. 11 presents cooling power curves. The simulation assumes 2.0 MPa average pressure and 30 Hz; the PV power is fixed at 70 W, and this is comparable to 100 W input power to the compressor.

The simulation reveals that with lower precooling temperature, T_{c2} will continue to decrease linearly, while in the experiments, the drop of T_{c2} became much slower at lower Tregmid temperatures. This may show that the loss calculation for the regenerator heat transfer differs considerably from the actual cases. This is due to the simple treatment of the regenerator in the simulation; it is treated as a single unit when the heat transfer is calculated.

Shown in Fig. 11 is the cooling power curve. In the simulation, the decrease of slope with increasing precooling temperature is evident, just like in the experiment, and the main reason is the heat transfer loss increases in the low-temperature part of the regenerator. In contrast, without the double-inlet, the slope has little change, and this is also similar to the experiments, though the slope in the experiments is still quite different from that in the simulation.

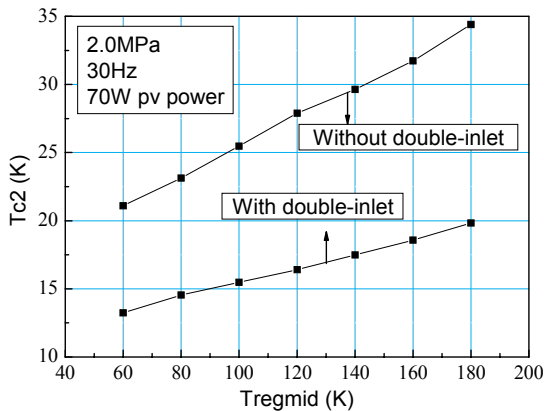


Figure 10. Simulating results of Tregmid vs. Tc2.

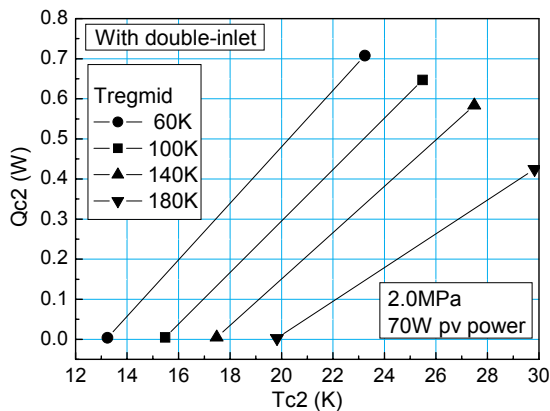


Figure 11. Simulating results of second stage cooling power change for different Tregmid.

Though the simulation reflects some features of the two-stage cooler, many improvements are needed to improve the model, especially the low-temperature heat transfer calculation in the regenerator.

CONCLUSIONS

Through experiments and analysis, three conclusions have been drawn:

1. By decreasing the fill pressure to 1.2 MPa, cooling temperatures as low as 12.80 K were able to be achieved with the present prototype at 30 Hz.
2. The study reveals that, though lower precooling temperature generally leads to better performance, when the precooling temperature is lower than a certain value, for example 120 K for low power or 100 K for high power, its impact on performance is small. When the precooling temperature is too high, it will result in an increase in the refrigeration temperature and a decrease in the cooling load slope; this is often reflected as a change in the temperature of the pulse tube wall.
3. The simulation reflected some of the feature of the experiments, but there is lot to be improved in the model, especially in the loss calculation.

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