Free Third-Stage Cooling for Two-Stage 4 K Pulse Tube Cryocooler

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ABSTRACT

The helium enthalpy variation with temperature and pressure in the operating range of 4K cryocoolers is by far different from an ideal gas. The real gas behavior leads to large irreversibility in the regenerator operation. It is theoretically possible to reduce these losses and recover some "free" cooling power by implementing heat intercepts in the regenerator. We have experimentally confirmed this opportunity with a commercial 4 K pulse tube. Several hundred mW of "free" cooling power in the temperature range of 6 K to 20 K has been obtained without any degradation in the initial cooling power at 4 K. The experimental set up is described and preliminary experimental results are presented and discussed.

INTRODUCTION

4 K pulse tube cryocoolers are the most promising coolers for low temperature superconductor (LTS) applications such as MRI, Magnetocardiography (MCG), SQUIDS, RSFQ or for the precooling of sub-Kelvin refrigerators due to the low level of generated vibrations and high lifetime. However, the 4 K pulse tube cryocoolers suffer from a relatively low efficiency due to high irreversibility in the regeneration process.

The irreversibility in the second stage regenerator is partly due to large temperature differences between high pressure and low pressure alternative flows. This is clearly illustrated in the Figure 1. In this figure, high pressure (20 bar) and low pressure (5 bar) enthalpy variations versus temperature are reported.

The enthalpy axis is scaled in arbitrary units. The purpose of this graph is to illustrate the phenomena. Both high and low pressure curves are arbitrarily set at the same value at 4 K, corresponding to a perfect regenerator with no temperature gradient at the cold end (an ideal case respecting the second law of thermodynamics: no temperature inversion between low and high pressure flow in the regenerator and ideal infinite specific heat regenerating material).

We can observe that between 6 K and about 20 K, a large temperature gradient is developed in the regenerator. The idea is to recover some cooling power in this temperature range by inserting a heat exchanger in the regenerator and reduce the temperature gradient in the next section of the regenerator.

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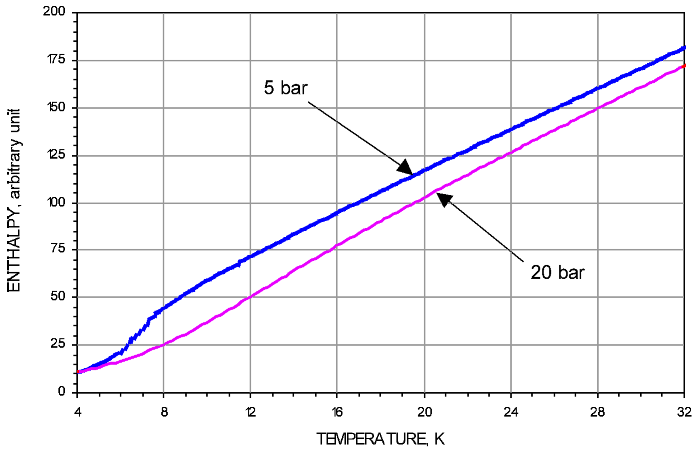


Figure 1. ^{4}He enthalpy curves at low and high pressures commonly used in a 4K pulse tube cooler.

This methodology for extracting cooling power from helium in a cooling system regenerator has been patented by Air Liquide (US Patent No. 6,915,642).

This aspect has already been analyzed theoretically and numerical calculations have shown that a significant "excess" cooling power can be produced in the 10-16 K temperature range.[1] This aspect is also well known by the Helium refrigeration community where cascade Joule-Thomson expansions are used to optimize cooling power recovery during gas expansion from HP to BP.

In the course of a PhD work related to the development of a dilution refrigerator in partnership with CNRS/CRTBT, we experienced this phenomena successfully by clamping some copper rings at various locations on the second regenerator of a PT405 type pulse tube cryocooler from CRYOMECH Inc. Two copper rings were attached at the middle and ¾ position of the regenerator at the 4K plate side. The experimental results were very encouraging. Beside the fact that some thermal gradients are inherent to the assembly method used, those rings are currently used for precooling of the dilution refrigerator for thermalization of the ^{3}He/^{4}He mixture flow.

ADVANCED PROTOTYPE

Based on the successful proof of concept with external heat intercepts, we notified Cryomech Inc. for the implementation of two silver brazed copper heat exchangers at the same locations as the one presented above. The advanced prototype, leading to a potentially commercially available product, is shown in the Fig. 2.

Performance of the modified 4 K pulse tube cryocooler

The performances reported herein are the preliminary tests results achieved by Cryomech Inc. prior to delivery of the cold head unit to Air Liquide. The compressor used was a CP950/60 Hz type connected with 7 meters long flexible lines to the cold head. The system filling pressure was 15 bars (220 psig). The insulation vacuum was 10^{-6} mbar, 4 layers MLI was used for the second stage as well as for the radiation shield and the first stage.

Figure 3 reports the performance test results with no load applied to the first stage, no load applied on the lower intercept and 0.5 W applied to the second stage. The temperature on the upper stage is plotted as function of the applied heat load at this location.

Figure 4 reports the test results for similar conditions except that 10 W heat load is applied on the first stage.

Figures 3 and 4 demonstrate that an appreciable cooling capacity is available at the upper intercept without degradation of the 2nd stage performance (4K stage). Depending on the load applied at the first stage, a free cooling capacity of 1 W is available at 6.91 K (Figure 3) or a free

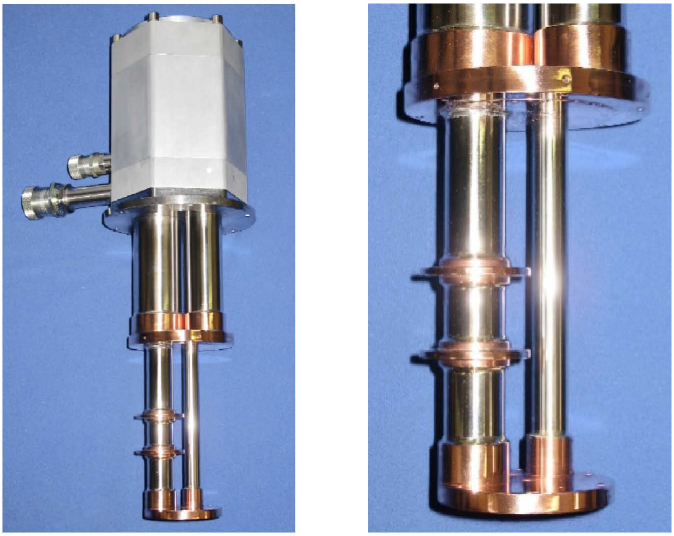


Figure 2. 2 stage PT405 pulse tube cooler with brazed heat exchangers.

cooling of 1 W is available at 8.25 K (Figure 4). Notice that a performance of 1 W at 8 K is the nominal performance of a PT810 type pulse tube cryocooler requiring 7 kW input power. It can then be concluded that with the implementation of the heat intercept we obtained the cumulated performance of a PT405 and a PT810 with only 5.5 kW input power (instead of 12.5 kW when considered separately). It is a significant improvement of the system efficiency.

It is also shown on Figure 3 and 4 that above a given amount of heat the equilibrium rapidly shifts towards a higher temperature level.

Finally some examples of test results are reported in the Fgure 5 for simultaneous applied heat loads on both stages and intercepts. The cooling power available at each stage and intercepts is included beside each location.

CONCLUSION

The possibility to reduce the regenerator losses and recover some “free” cooling power by implementing heat intercepts in the regenerator of a 4 K two stage pulse tube cooler has been

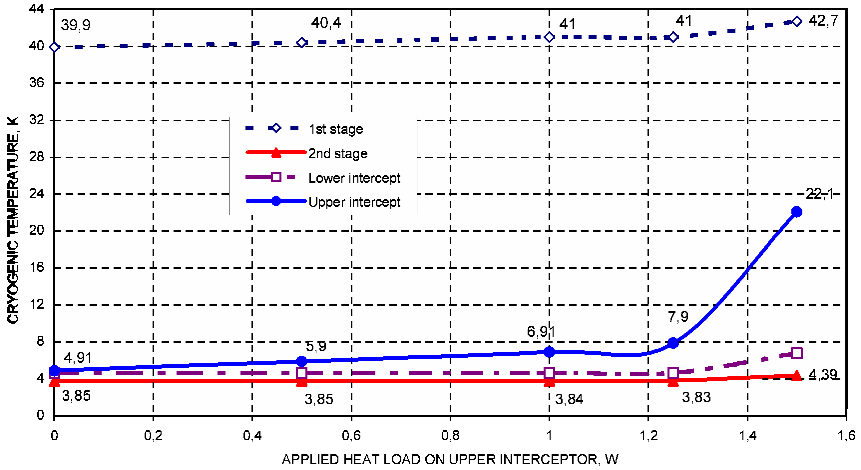


Figure 3. Performance test results with no-load applied on the 1st stage and lower intercept, 0.5W applied on the 2nd stage. 5.5 kW input power.

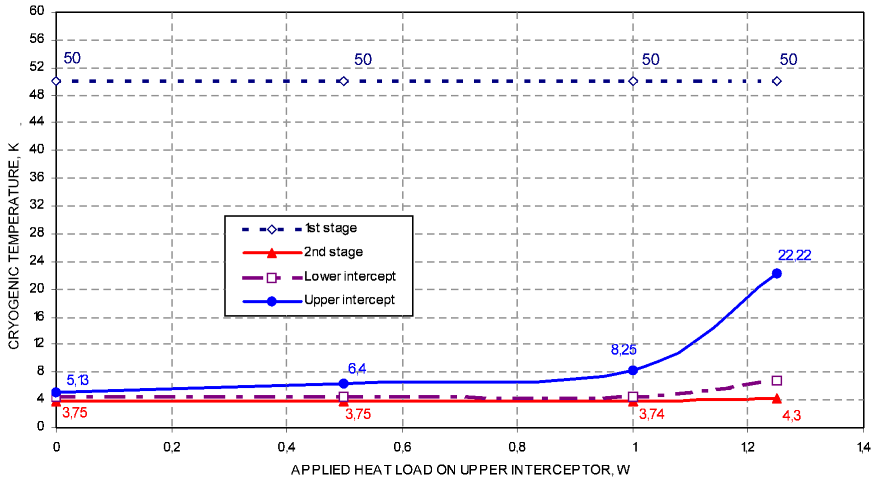
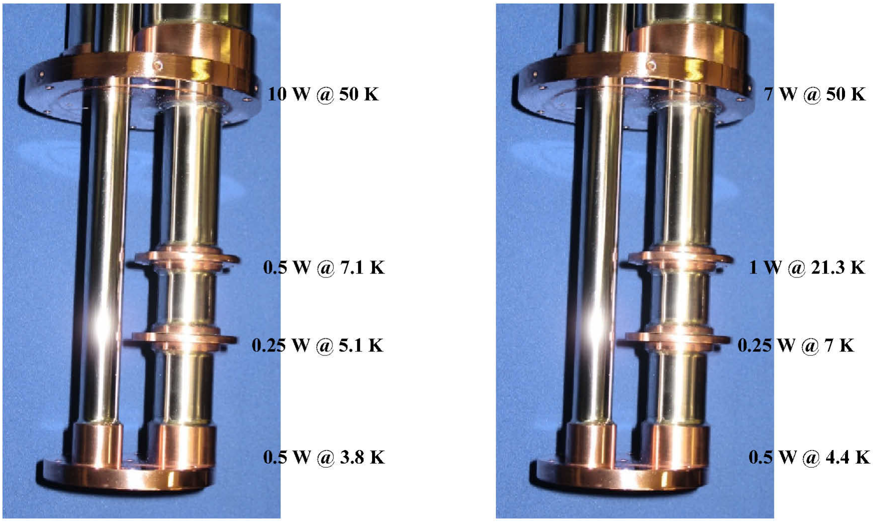


Figure 4. Performance test results with 10 W applied on the 1st stage, no-load on the lower intercept and 0.5W applied on the 2nd stage. 5.5 kW input power.



(a) (b)

Figure 5. Performance with various loads applied simultaneously on both stages and intercepts. 5.5 kW input power.

demonstrated successfully. The required modification of the existing 4 K pulse tube coolers is simple. The demonstrated free cooling power should lead to a significant improvement in system efficiency during the integration of this type of cooler. The cooler can be considered for numerous applications, which is the purpose of Air Liquide patent.

Additional tests are continuing at Air Liquide with CP970/50Hz type compressor with a system filling pressure of 13 bars (190 psig).

ACKNOWLEDGMENTS

The authors want to acknowledge the collaboration and interest of CRYOMECH in implementing the heat intercepts in their standard PT 405 Pulse Tube Cryorefrigerator to demonstrate a direct comparison between an existing product and our patented architecture.

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