30 W at 50 K Single-Stage Coaxial Pulse-Tube Cooler with Tapered Buffer Tube

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ABSTRACT

The performance of large-capacity single-stage pulse-tube coolers at temperatures below 70 K is often hampered by Rayleigh streaming, or the natural boundary-layer convection that occurs in the buffer tube ('pulse tube'). In Olson and Swift's landmark 1997 paper[1], they explained how a slight taper in the buffer tube could suppress this streaming. They also showed how the streaming could be suppressed by the proper phasing of pressure vs. flow in the buffer tube, which is enforced by the proper choice of phase-shift mechanism (i.e. length and diameter of inertance tube, etc.). This is the approach usually taken because a straight buffer tube is simpler, especially when considering a coaxial construction (where a tapered buffer tube would imply a tapered regenerator). In addition, the phasing which suppresses Rayleigh streaming coincides with efficient cycle phasing for many applications. At temperatures below 70 K, however, this is less true, and for a 50 K machine a significant benefit may be realized by decoupling the streaming suppression from the cycle phasing. At the same time, we have found that coaxial coldheads can successfully use nonconductive buffer tubes, if the material with the right thermal expansion coefficient is selected. This enables the use of a tapered buffer tube in a coax design, as the material can be thick enough to have a constant outside diameter (OD) and a tapered inside diameter (ID). This paper will discuss the results obtained on a high-capacity cooler using a tapered buffer tube and includes some measurements showing the importance of having the right taper angle.

INTRODUCTION

Large (input power 2 kWe) high-frequency (>40 Hz) pulse tube coolers[2] have had increasing success in recent years, reaching capacities as high as 1000 W at 77 K. In such large coolers, the Rayleigh streaming can be a very significant parasitic loss, which becomes more significant as the temperature approaches the cooler's ultimate temperature; in this situation the gross cooling of the cooler is relatively small and the streaming penalty is greater. Thus, suppression of the Rayleigh streaming is absolutely necessary for operation near a large pulse-tube cooler's ultimate temperature. At the same time, the phase shift necessary for efficient operation increases at lower temperatures. It is therefore at least theoretically advantageous to suppress the streaming by using a tapered buffer tube, and choose the cycle phasing independently.

The awkwardness of a tapered buffer tube in a coaxial coldfinger can be overcome by using a thick-walled, nonconductive material, since the buffer tube is not part of the pressure vessel. We have found that Garolite XX is a suitable material for buffer tubes, as its thermal expansion coeffi-

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cient matches stainless steel well enough to avoid gaps forming between the regenerator screens and the buffer tube at low temperatures. The construction of the coldhead in this project is very similar to other coldheads made with Garolite buffer tubes, except that the buffer tubes in prior projects were not tapered[3].

RESULTS

First tests with 1.6-degree taper

According to our simulations, based on our first-pass cooler design, we found that merely a 1.6 degree taper would be sufficient to suppress Rayleigh streaming, when the phasing between pressure and flow in the buffer tube was 65 degrees (as opposed to the 50 degrees required to suppress streaming in a straight buffer tube.) To our dismay, the cooler only reached an ultimate temperature of 65 K. Subsequent careful review of all the parts and drawings showed that the final design had evolved far enough away from the initial design that the 1.6 degree taper was no longer adequate.

To confirm this theory, we did a series of heat-load tests at moderate temperature (86 K) with constant input power (2 kWe), while varying frequency. Varying frequency changes the phasing in the buffer tube, and if there is Rayleigh streaming present, the cooling power results should be very sensitive to frequency. The results are shown in Figure 1.

Acoustic pressure and pressure phase measurements in the inlet to the inertance tube and in the compliance tank were used in conjunction with Sage[4] to estimate the acoustic field in the buffer tube. These results in turn were used with the formula for streaming suppression derived by Olson and Swift[1] to estimate at what point in the buffer tube streaming is suppressed (if at all). It may just be coincidence, but the maximum cooling power in Figure 1 occurs when the streaming suppression point is right in the center of the buffer tube (50% of length). At lower frequencies, the simulation suggests that cooling power should keep increasing, but the dotted line suggests that the streaming suppression point is moving too close to the cold end to be useful.

Tests with 2.7-degree taper

We subsequently replaced the original buffer tube with a new one having a 2.7-degree taper, and re-optimized the inertance tube to place the coldhead in its theoretical "sweet spot." The results were immediately, dramatically better, as shown in Figure 2.

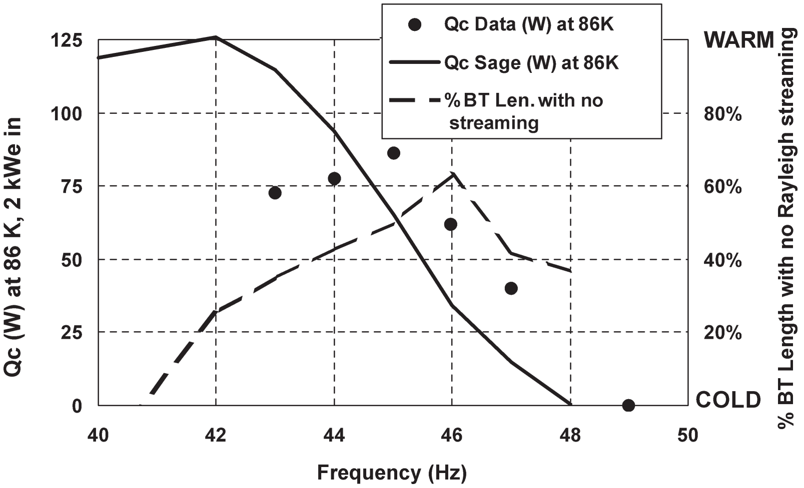

Figure 1. Heat-load tests of "2S226K" cryocooler as a function of frequency, with 2 kWe input, with the 1.6-degree tapered buffer tube.

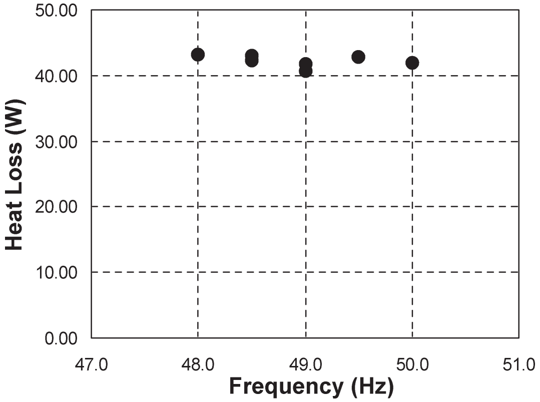

Figure 2. Heat-load tests of “2S226K” cryocooler as a function of frequency, with 2.75 kWe input, at 50 K, with the 2.7-degree tapered buffer tube.

Not only does the cooler attain significant cooling power at 50 K, as designed, but the sensitivity to frequency has been vastly diminished. This demonstrates the importance of getting the taper angle just right.

Tests in final configuration

Figure 3 shows the cryocooler in its final configuration, with compact inertance tube and compliance tank on top of the coldhead. For scale, note that the cabinet’s long dimension is about 30 inches.

The 2S226K is configured for push-button operation, with automatic temperature control. In this configuration, the performance was initially similar to the lab tests, but eventually we discovered that when run for very long periods in steady-state, the cooling power would degrade for input powers above 2.1 kWe. For that operating point, we obtained 30 W of cooling at 50 K, enough to serve the intended application, However, there are apparently amplitude-dependent effects that we do not understand. If these were better understood, the capacity of the cooler could perhaps be significantly greater.

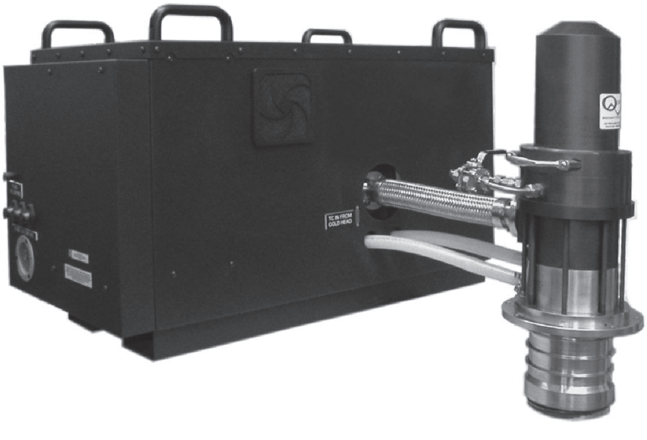

Figure 3. Final configuration of 2S226K cryocooler, with 30 W of cooling power at 50 K, for 2.1 kWe input, at 48 Hz. Long dimension of cabinet is approximately 30 inches; weight is 102 kg.

CONCLUSIONS

The present work has shown that a single-stage ‘pulse-tube’ with high capacity (30 W) can attain reasonable efficiency at 50 K (~8% of Carnot) and that a tapered buffer tube can be a useful means of streaming suppression, allowing the cycle phasing to be optimized separately. However, at high amplitudes, there are some effects limiting the performance that are not yet understood. Some non-uniformity of the temperature around the circumference of the regenerator has been observed to roughly correlate with the degraded performance at high amplitudes. It has been suggested that perhaps intermittent copper screens or even perforated copper (annular) disks in the regenerator could help maintain temperature uniformity, and perhaps prevent the regenerator from developing anomalous behavior. It might also be of interest to look carefully at the flow field in the buffer tube (perhaps with CFD) with and without taper. A cursory look at the residuals in the Olson/Swift formula suggest that perhaps in a tapered buffer tube, the streaming on either side of the ‘dead zone’ may be more vigorous than in a straight buffer tube, increasing the risk of convection loss.

ACKNOWLEDGMENTS

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4. Sage is a software package for analyzing Stirling and similar devices, available from Gedeon Associates, Athens, Ohio.