Toward an 1800-liter Self-Sustaining Biological Freezer, Enabled by Twin PWGs ‘Overdriving’ a Pulse Tube Coldhead

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ABSTRACT

MVE Biological Solutions, makers of the Fusion self-sustaining 1500-liter biological freezer, have recently demonstrated the feasibility of a larger 1800-liter model. The larger freezer is enabled by a cryocooler with approximately double the cooling capacity of the original Fusion. To leverage existing components and reduce the development cycle, the cryocooler configuration consists of the same coldhead used in the existing Fusion cryocooler, driven by two Fusion pressure-wave generators (PWG’s) in tandem. This concept carries at least two technical risks: first, that the twin PWGs might not operate in perfect synchronization if they are mismatched, and second, that higher amplitude in the coldhead might degrade performance due to nonlinear effects. Though such amplitude effects have been observed in larger-scale coldheads (with capacity of ~200W at 80K) prior experience suggests these smaller coldheads, with nominal capacity of ~30W at 80K, might be relatively immune. Preliminary data suggest that little or no degradation results from “overdriving” the Fusion coldhead, with twice the cooling capacity obtained from twice the acoustic power input.

INTRODUCTION

In 2017, MVE Biological Solutions (then a part of Chart Industries) introduced the Fusion, the world’s first self-sustaining biological freezer[1]. Featuring an efficient Dewar for sample storage, an inner pressure vessel with a charge of liquid nitrogen, and a pulse-tube cryocooler for reliquefying the nitrogen as it boils off, it combines the convenience of an “ultra-low” cabinet freezer with the lower storage temperature and hold time of a traditional Dewar-style LN_2 biological freezer.

The inaugural Fusion product is based on a 1500-liter storage Dewar, but there is interest in self-sustaining freezers of other sizes, such as an 800-liter version (for easy passage through standard doorways) and an 1800-liter version, for greater storage capacity. Adapting the technology to a smaller Dewar is straightforward, but the larger Dewar has a greater heat leak than the 1500-liter size, and will require more cooling power than the Fusion cryocooler can easily supply.

Rather than develop a new cryocooler size, especially without knowing the real market demand for the larger freezers, MVE has experimented with configuring existing parts to obtain more cooling capacity, specifically, driving a single Fusion coldhead with two tandem Fusion pressure-wave generators (PWGs). The hope is that the cooling power will approximately double, if the PWGs are able to deliver double the acoustic work to a single coldhead and the coldhead responds linearly to the increased drive power.

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POTENTIAL RISKS OF TANDEM PWGs DRIVING SINGLE COLDHEAD

PWG mismatch

One risk is that the PWGs will not run at the same amplitude, or even the same phase, given the same excitation. Supplying them with customized voltages, or worse, customized time-delayed waveforms, would complicate the control system considerably. The approach taken is to match the PWG parameters as closely as possible to mitigate this risk. . An interesting question, especially for manufacturing in quantity, is how closely the parameters must match to permit driving both at the same nominal voltage and phase. We did not attempt to answer that question in this study.

Nonlinear response of coldhead to high acoustic amplitude

Another risk is that the Fusion pulse-tube coldheads will not respond linearly to large increases in acoustic amplitude. If power is roughly proportional to amplitude squared, then doubling the power into the cryocooler increases the amplitude over 40%, a large increase over the design point.

Among the specific nonlinearities that might cause trouble are (1) enhanced flow resistance in the inertance/compliance network caused by higher flow velocities, and (2) flow disruptions in the thermal buffer tube (pulse tube), seeded by small manufacturing flaws, that will cause warm and cold gas to mix. It is this second phenomenon that poses the most concern, since it is hard to predict and could vary significantly from one coldhead to another.

Experience with high-capacity coldheads. We have prior experience[2] measuring cooling capacity of much larger pulse-tube coldheads (6-inch diameter, capacity ~200W at 80K) as a function of input power and acoustic amplitude, for the purpose of predicting how several of them together will fare in a system with a much larger power acoustic driver.

In this higher-power system, integrating the coldheads is nontrivial, and there is no way to test them with controlled electric heat loads *in situ*. Therefore we want to have some idea how they will perform at high power *befor*e they are integrated. In the absence of a high-power driver, our strategy has been to drive the coldheads on a smaller driver, starting at low power and taking measurements at successively higher powers, ending at the maximum feasible with the smaller driver. We then extrapolate from these results to estimate how each coldhead will perform in the higher-power system. Figure 1 shows the “2S241K” cryocooler system on the left, suitable for driving individual coldheads and testing them under controlled lab conditions. The “2S362K” system is shown on the right, where three of the “241”-size coldheads are integrated into a custom 3-bucket Dewar for liquefying oxygen.

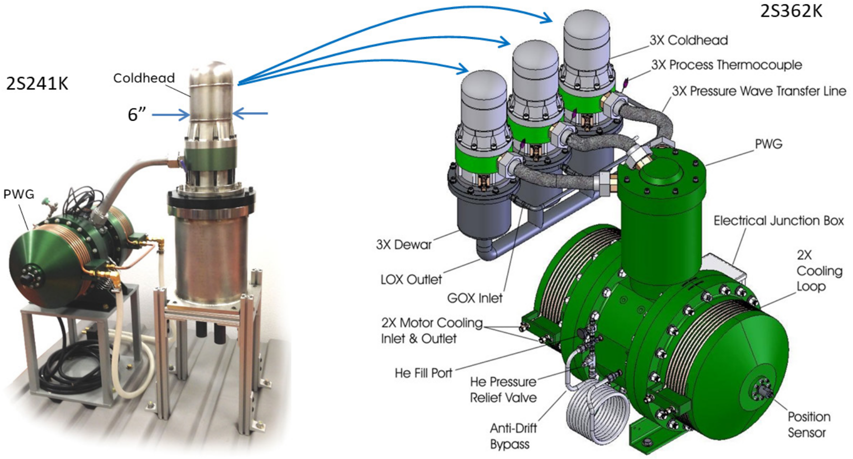

Figure 1. Large pulse-tube cryocoolers, where amplitude effects in coldheads have been studied. The 2S241K, left, is rated at 200W at 80K for 4 kWe input; the 2S362K is rated for 1600W at 100K for 18 kWe input.

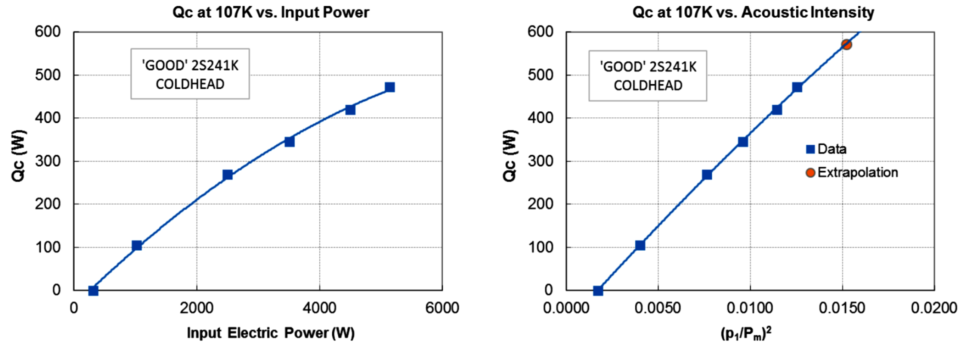

Figure 2. Data for 2S241K coldhead that responds linearly to increased acoustic power.

Some of the coldheads tested this way, even those that perform reasonably well at their design amplitude, have diminishing returns at higher amplitude. Figure 2 shows data for a well-performing coldhead, where the increase in capacity is nearly linear with acoustic intensity[3]. This coldhead reaches nearly 400W at 107K at the 2S241K design point of 4 kWe into the PWG and $(p_1/P_m)^2 = 0.012$ into the coldhead. Its response with increasing $(p_1/P_m)^2$ is linear enough for a comfortable extrapolation to the amplitude it will experience in the 2S362K, or just above $(p_1/P_m)^2 = 0.015$.

By contrast, consider the data presented in Figure 3. Figure 3 shows two coldheads with distinct curvature in their capacity data as they reach high amplitude. "Bad" coldhead #1 is particularly interesting because its capacity at the nominal level of $(p_1/P_m)^2 = 0.012$ is comparable to the "good" coldhead in Figure 2, but it quickly loses ground as $(p_1/P_m)^2$ increases. What's also notable is that there were no obvious physical flaws in either of the 'bad' coldheads. Based on the comparison to other coldheads manufactured in the same time period and with the same practices, we believe that we are looking at turbulence in the buffer tube seeded by small gaps or occlusions that are not obvious to the eye. Unfortunately, in these large coaxial coldheads, the buffer tube itself is not easily accessible for instrumentation, and there is no more sensitive measure of flow uniformity in these coldheads than the cooling capacity itself.

In any case, our previous experience established that a pulse-tube coldhead can perform perfectly well at its design point, but fail at higher amplitudes, for reasons not easily foreseen at the time of manufacture.

Reasons for optimism when 'overdriving' Fusion coldheads

Common sense, and our experience with verified buffer-tube turbulence, tells us that flow uniformity is harder to enforce as the aspect ratio of the coldhead (*L/d*) decreases. Our Fusion and

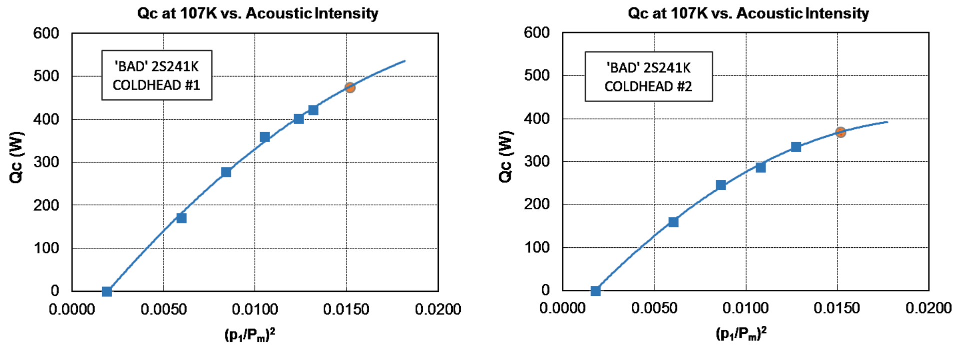

Figure 3. Data for 2S241K coldheads with capacity that rolls off at high amplitude.

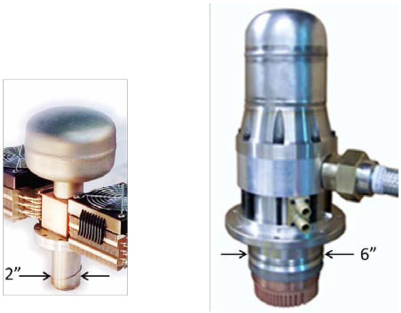

Figure 4. Fusion coldhead (left), featuring heat-pipe CPU heatsinks for heat rejection, and 2S241K coldhead (right), with finned copper attachment on the coldtip to enhance surface area for oxygen liquefaction.

2S241K coldheads have nearly the same length regenerator (which is mostly a function of temperature span, working fluid, and frequency) but the Fusion coldhead is 1/3rd of the diameter, as illustrated in Figure 4. This alone does not prove the Fusion coldhead is below the threshold for buffer-tube disturbance (or other nonlinear mischief) at high amplitude, especially since we are not increasing $(p_1/P_m)^2$ by a mere 25% above the design point (as with the 2S241K) but doubling it. However, we have another reason to believe the higher power point will be safe.

Higher cold-tip temperature T_C leads to higher $(p_1/P_m)^2$. One acoustic aspect of pulse-tube coolers that will be familiar to anyone with experience simulating and testing them is that the acoustic pressure-drop across the regenerator is lower as the process temperature (cold-end temperature) rises, given the same reject temperature and input power. The impedance of the coldhead looks more reactive as ΔT decreases. At the same time, to maintain the same acoustic power input, the pressure wave amplitude on the warm end must rise. Thus the acoustic amplitude in the buffer tube rises significantly as a function of process temperature, for constant power input. By choosing the right cold-end temperature in an experiment, we can create the same acoustic drive level in the buffer tube that the coldhead would experience at our normal target temperature with twice the acoustic power going in, using a single driver at its normal maximum. Figure 5 shows a Sage[4] simulation of the pressure wave in the pulse tube, as a function of both the input power at constant T_C and as a function of T_C at constant power. At least according to the Sage simulation, the expected pressure wave in the buffer tube at T_C = 86K and 1200 watts input to the cryocooler is matched by running the system at 600 watts input and with T_C = 200K.

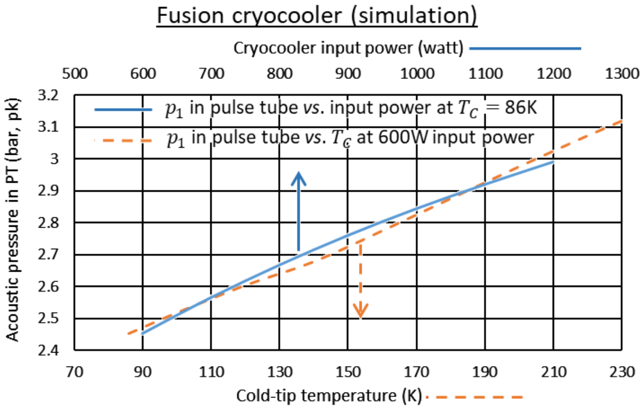

Figure 5. Simulated pressure wave amplitude in pulse tube of Fusion coldhead, for both fixed cold-tip temperature and varying input power (solid curve) and fixed input power and varying cold-tip temperature (dotted curve).

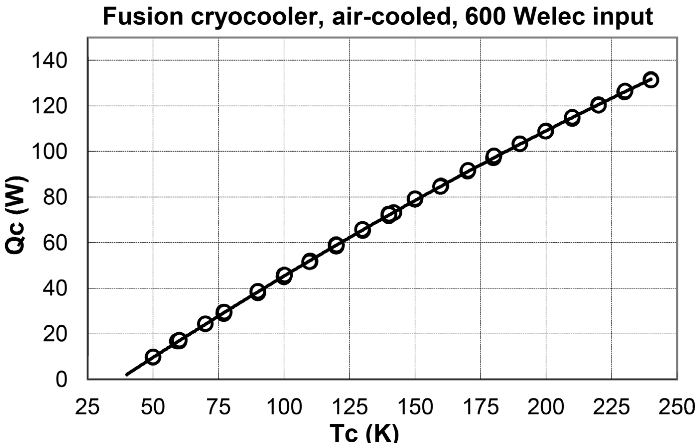

Figure 6. An example of a Fusion cryocooler load curve, spanning a large range of temperatures, showing no ill effects of driving the pulse tube over 50% higher in amplitude than its design point.

Thus, by running the cryocooler at an elevated cold-tip temperature near 200K, we can mimic the drive level in the pulse tube at 1200 watts into the cryocooler. The one critical difference between the two situations is that at the higher T_C, the temperature gradient in the pulse-tube is lower than normal. While we don't know for sure how this will affect the results, there is some reason to believe that a higher gradient is more stabilizing as long as the cold end is down[5], making the higher T_C test even more aggressive at detecting nonlinear roll-off in cooling capacity[6].

Existing data for $Q_C(T)$ can be used to observe high $(p_1/P_m)^2$ behavior. As part of product development, a number of Fusion cryocoolers have been tested over a wide range of cold-tip temperatures, and given the relationship between $(p_1/P_m)^2$ and T_C discussed above, these data already collected can be used to predict how the Fusion coldhead might behave when overdriven.

Figure 6 shows one such cryocooler test, where the data include coldtip temperatures up to 200K and beyond. There is some gentle curvature, but nothing dramatic occurs at the higher coldtip temperatures, and the performance at 230K or 240K is easily extrapolated from the data at 200K and below. This suggests to us that the Fusion coldhead might well tolerate being driven at 86K and twice its nominal power, or even higher, without any significant artifacts.

EXPERIMENTAL PROTOTYPE

Prototype hardware based on solid model

Figure 7 shows a rendering of how two PWGs driving one coldhead might be integrated with an 1800-liter freezer. The large rectangular objects on either side of the coldhead are thermosiphon CPU heatsinks, for heat rejection. The footprint of the freezer is large enough that the two PWGs and the extra plumbing fit comfortably on the top. The prototype hardware is designed to approximate these same dimensions.

Figure 8 shows our first experimental prototype setup, with water-cooled blocks clamped on to the heat-rejection surfaces of the coldhead. The drive electronics and instrumentation are not visible in this view, but since the system is designed to run at 60 Hz, the PWGs are run directly with variable transformers. Because we are doing initial experiments, we allow ourselves to run each PWG with a distinct voltage, although this may not be ideal for a product. We have also run this particular system with the same voltage on both PWGs, and the difference in performance is slight.

Dynamic matching. When one coldhead is driven by two PWGs, each one contributes half the volume flow for a given pressure wave, which makes the impedance seen by each PWG approximately double the impedance of the coldhead as seen by a single PWG. This raises the natural

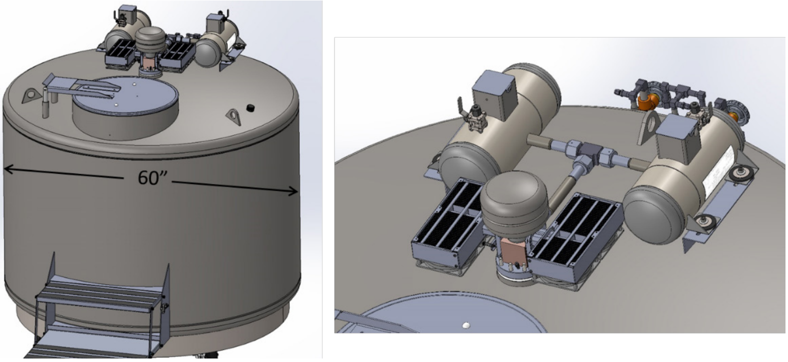

Figure 7. Solid-model rendering of how twin-PWGs driving a single coldhead might look on an 1800-liter freezer. The large boxy objects on either side of the coldhead are thermosiphon CPU coolers for heat rejection.

Figure 8. Experimental setup, mimicking the layout in Figure 7 but with water cooling (for now).

frequency of the system. To preserve 60Hz resonance, the motors in these PWGs are built with brass pistons instead of aluminum. This simple material swap, without changing the piston size or any other PWG parameter, restores the impedance match. Thus the parts in the smaller-size Fusion freezers aren’t *completely* interchangeable with the proposed 1800-liter version.

Results. Figure 9 shows some results from the first prototype. Cooling power at 86K and 1200 watts input to the system (65W) is *nearly* double the capacity at 600 watts (35W), though there is definite curvature. However, a plot of Q_C versus $(p_1/P_m)^2$ *at the coldhead* is very linear:

The linearity of the results in Figure 10, all the way from no-load to 1200 watts input power, indicates that the coldhead itself is responding linearly. Measurements of acoustic pressure at the PWGs suggests there are nonlinear acoustic losses in the ductwork between the PWGs and the coldhead. This is an area where improvement is possible; smoother transitions will lead to more efficient acoustic transmission, which must be weighed against higher parts cost.

CONCLUSION

This work has demonstrated that MVE’s Fusion pulse-tube coldhead, with approximately 30W nominal cooling power at 77K, can double its capacity by being driven with twice the acoustic

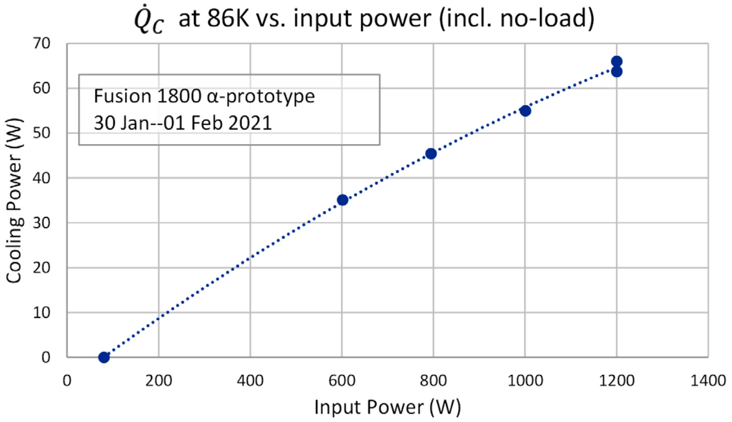

Figure 9. Data from Fusion 1800 prototype, showing cooling power versus input power.

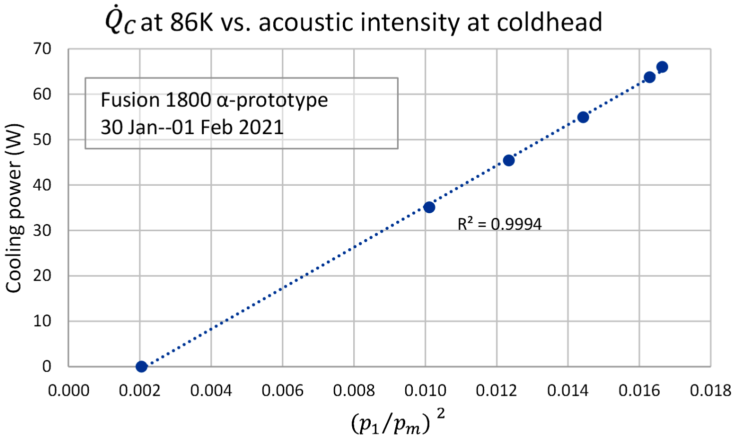

Figure 10. Data from Fusion 1800 prototype, showing cooling power versus $(p_1/P_m)^2$.

power input without nonlinear effects reducing the capacity at higher amplitudes. These results are consistent with the behavior of these coldheads at elevated coldtip temperatures, where the acoustic amplitude in the buffer tube (pulse tube) is also much higher than normal and no performance anomalies are observed. This is a sample size of one, of course, so more tests and more prototypes will be needed to fully validate this conclusion.

The doubling of acoustic power input can be achieved with two standard twin-linear-motor pressure-wave generators driving in tandem, without any special effort required to synchronize them. The two PWGs can be dynamically matched to the single coldhead by a simple material change to the pistons. It is therefore feasible to use nearly all standard parts already in production for the Fusion 1500 liter freezer to make a cryocooler appropriately sized for the larger 1800-liter freezer. In order for the 1800-liter system to match the overall efficiency of the original 1500-liter system, however, acoustic losses in the connections between the PWGs and the coldhead may have to be reduced.

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2. Spoor, P. S., “Large >60 gallon/day ‘pulse-tube’ oxygen liquefier for aircraft carriers,” *Proceedings of the Cryogenic Engineering Conference (CEC) 2015, IOP Conf. Series: Materials Science and Engineering,* vol. 101**,** IOP Publishing, Bristol (2015)**.**
3. We refer to “acoustic intensity” in the text, but the non-dimensional quantity shown in the graphs is more properly referred to by the longer, more awkward phrase “square of the normalized acoustic amplitude,” or $(p_1/P_m)^2$.
4. Sage software to model and optimize Stirling cycle engines and coolers, pulse-tube cryocoolers, and other types of cryocoolers, created and distributed by Gedeon Associates, Athens, Ohio *https://www.sageofathens.com.*
5. Swift, G.W. and Backhaus, S., “Why High-Frequency Pulse Tubes Can Be Tipped,” *Cryocoolers 16,* ICC Press, Boulder (2011), pp. 183-192.
6. Any convection will carry a smaller penalty for a given mass flow. The net effect is hard to predict.