Acoustic-Stirling 55 Gal/Day Oxygen Liquefier for Use on Aircraft Carriers

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ABSTRACT

This paper describes an acoustic-Stirling oxygen liquefier being built for the U. S. Navy's newest aircraft carrier. It has an intended capacity of 55 or more gallons of Liquid Oxygen per day, or a heat-load equivalent of approximately 1,000 W continuous in the range of 90K to 106K. The design philosophy is explained, and some of the important technical risks are discussed. Data on the full system are not yet available, but some test data on key components are presented.

INTRODUCTION

The advent of large-capacity acoustic-Stirling (sometimes called Stirling-type 'pulse-tube') coolers[1,2] has made it possible to envision quiet, reliable, efficient production of liquid oxygen "on demand" for medium scale applications such as shipboard medical use. The Navy has specified acoustic-Stirling as the preferred cooling technology for producing Liquid Oxygen (LOX) aboard the next generation of aircraft carriers, the CVN-21 class, starting with the first of this class, CVN-78. CFIC-Qdrive has been selected (as a subcontractor) to supply the cooler for the LOX system, partly based on the success of the USAF's "DOLS" (Deployable Oxygen Liquefier System) project. For DOLS, CFIC-Qdrive built an acoustic-Stirling system that produced 2 liters/hour of LOX from approximately 3.5 kWe input, with quiet, push-button operation. The USAF did not ultimately choose to deploy oxygen liquefiers, opting for compressed bottled oxygen instead; but the Navy, which already uses shipboard liquefiers (of the reverse-Brayton / Joule Thomson type), has elected to support development of an improved oxygen liquefier for its new carriers. In particular, they are attracted to the relatively short time between start-up and delivery (minutes) offered by the acoustic-Stirling system, compared with the existing systems (hours).

CHOICE OF CONFIGURATION

The required capacity of the Navy LOX system, 55 gallons per day, or ~1,000 W at ~100 K, is similar to the performance of the largest-capacity acoustic-Stirling cryocooler known to us.[1] This system uses a CFIC twin-motor pressure-wave generator (PWG) driving an "in-line" acoustic-Stirling coldhead (made by Praxair, Inc.), and has produced 1,000 W of cooling at 77K, from approximately 20 kWe input. This system is intended for nitrogen cooling/subcooling for HTS applications; but since oxygen liquefies at 90K (or higher, if pressurized), this same system would have even more capacity if used as an oxygen liquefier. Thus it would seem like a good fit for the CVN-21 carrier LOX system. However, a "cold finger" geometry is preferred over an 'in-line' head, especially an in-line that uses a shell-and-tube heat exchanger. The shell-and-tube is a very efficient type of heat exchanger for a liquefaction process, but it is exceptionally sensitive to fouling due to

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impurities such as argon (which freezes just below 90K), CO_2, and water. Furthermore, in order to achieve reasonable production costs, it is better to have a common platform for most or all applications beyond shipboard oxygen liquefaction. Most other applications, such as HTS cooling, cryopumping, etc., can more readily integrate a cold-finger coldhead design. CFIC is already engaged in developing HTS coldfingers for DOE; so it makes sense to use coldfingers in the oxygen liquefier as well.

However, since these will be the first acoustic-Stirling coldfingers of such a large capacity ever built, there is some technical risk. In particular, a coldfinger design carries a higher risk of inhomogeneous flow distribution than an in-line design, since the direction of flow must be reversed in the cold end. This risk is greater as the capacity of the coldhead increases. In general, the length of the critical thermal components in an acoustic-Stirling coldhead is determined by the frequency of operation, the working fluid, the temperature span, and to a lesser extent the charge pressure. Hence the heads tend to increase in diameter but not in length as their capacity increases. This decreasing *l/d* ratio increases the chances of uneven flow distribution in the regenerator or buffer tube.

One Drive, Multiple Heads

To alleviate the technical risk somewhat, CFIC decided to build the first prototype with multiple coldfingers on a single acoustic drive (the same type of drive used in the Praxair HTS system). The individual coldfingers are smaller than one single head would have to be. The risk that any one head might perform better and "run away" from its neighbors (i.e., experience positive feedback by consuming an ever-increasing share of the available pV work) is relatively small since all three cold-tips will be immersed in condensing oxygen and cannot be too far apart in cold-tip temperature.

Figure 1 shows a solid model rendering of what the assembled liquefier will look like (with two sides and the top of the cabinet missing). All three heads are attached to the acoustic drive (the "pressure wave generator," or PWG) with short transfer lines; the combination is very close to the impedance the PWG expects to see if it were driving a single head designed for 1000 W cooling at 77 K. Figure 2 shows a cutaway view of one coldhead (on its side). The buffer tube is made of relatively thick-walled G10; the idea here is that (a) the axial conduction will be very small, and (b) the buffer tube *could* be tapered in order to combat Rayleigh streaming. One can also suppress Rayleigh streaming with the appropriate choice of inertance and compliance; but it is at least conceivable that the terminating impedance that best suits the *cycle* is not the one that suppresses streaming. According to our simulations, this appears to be the case for lower cold-tip temperatures, e.g. 50 K to 70 K. At 90 K and above, the impedance of zero streaming (with a straight buffer tube) and the impedance of best cycle performance appear to be nearly the same.

Figure 3 shows the estimated performance of the system, for a couple of different reject temperatures. This graph incidentally illustrates one of the advantages of carrier deployment: the avail-

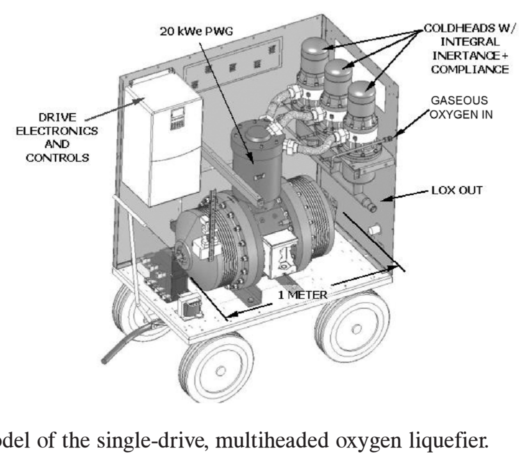

Figure 1. Solid model of the single-drive, multiheaded oxygen liquefier.

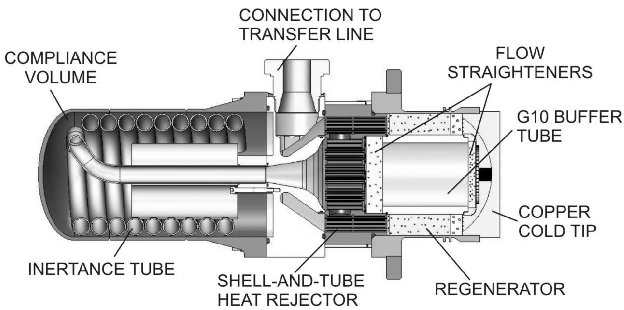

Figure 2. Cutaway view of the cold head design used in the multi-head liquefier of Figure 1, shown on its side for ease of display in the manuscript. The coldhead is intended for cold-tip-down orientation. For scale, note that the flow straighteners are 3.25 inches diameter.

ability of chilled water. In industrial applications on land, we have to be prepared to reject heat via closed-loop fin/fan units, where the coolant temperature can easily rise above 40°C. Here, the water is between 12°C and 21°C (or at least, that is the target spec), so we gain on performance over a land installation (besides saving money and space on the heat-rejection apparatus which isn't required). The existence of chilled water also gives us the option of driving our system a little harder than we might normally. The two limits we have to observe are the current limit and the stroke limit of the motors. The stroke limit is quite literally a hard limit, which cannot be exceeded. The current limit is actually a thermal limit; when we have a lower reject temperature, we can run with current over the nominal maximum, giving us a little bit of power headroom

While we don't believe that we will capture all the performance predicted in Figure 3, it appears that if we can run near 50 psig process pressure, and only get 50% of our predicted capacity, we will still meet the target.

COMPONENT TESTING

As of this writing, the coldheads themselves have yet to be completed, so there are no performance data on the whole system. We do have some data on subsystems and components that may be of interest.

Pressure-Wave Generator Testing

The pressure-wave generator, which supplies the pV work to run the Stirling cycle, has been tested to determine the magnitudes of its internal losses, and the resulting electric-to-pV efficiency

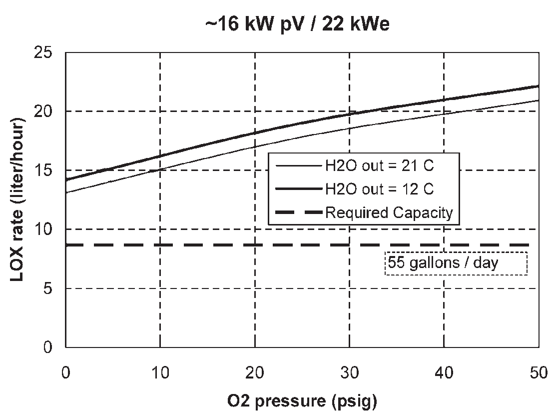

Figure 3. Preliminary performance estimate of multihead liquefier.

is predicted to be 75%, which is encouraging. The efficiency in a PWG this size depends very strongly on the effective magnitude of the radial gap between the piston and the piston bore, which can be artificially high if the motors are not centered in the gap, even if the gap is on average is very small. It can be challenging to achieve a radial gap less than 50 microns on a 246 mm diameter piston, suspended by flexures that are carrying a total moving mass of 17 kg.

Even more encouraging than the efficiency was the nearly zero piston drift encountered in this unit. All free-piston devices are susceptible to piston drift, particularly those with large pistons that operate against unequal pressure wave amplitudes between front and back sides of the piston(s). This unit is equipped with specially shaped pistons which, due to radial flexing in response to oscillating pressure, turn the clearance gaps into weak check valves that oppose the natural flux of working fluid from the front to the back side of the pistons. In addition, this unit has an approximate quarter-wavelength-long coiled tube that connects the front and back sides. This bypass tube forms a low resistance path for DC flow, but a high-impedance path for ac flow, helping to relieve any residual DC pressure difference that may remain even with the specially shaped pistons. It only takes ½ psi difference across the pistons to make them drift by a millimeter; yet the drift in this unit was well under 0.5 mm all the way from 0 to 4 bar peak, with a half-inch OD bypass tube in place.

Flow straightener testing

Since flow uniformity (particularly in the buffer tube) is so crucial in these coldheads, we have undertaken to qualify some of the flow straigheners we are considering. The default for flow straighteners is stacks of plain-weave screens, with alternating screens rotated 45 degrees to avoid a Moire pattern of mesh alignment. For flow straighteners of this large diameter (3.25 inches) the stacks are made of bronze and sintered together for extra mechanical strength. These constructions are very likely to have uniform flow characteristics, and effectively dissipate spatial variations in flow; but they are also fairly expensive to produce. Anything made of stacks of screens involves a lot of wasted material, and many process steps. As an alternative, we have considered sintered "hockey pucks" of randomly oriented copper fibers. We undertook to qualify their performance before committing to them in the coldhead assemblies. We built a test rig of PVC pipe, fed by a high-flow, low pressure air blower, with a stack of copper screens halfway up the pipe to straighten the flow before it encountered the test piece. The velocity of the flow just above the surface of the sample was measured with a hot-wire anemometer, with the results for two of the many samples shown in Figure 4. Clearly, the sintered fiber straightener has disturbingly non-uniform flow, even while it has a higher pressure drop than the screen stack. For the time being, we will be forced to stay with the stacked-screen straighteners.

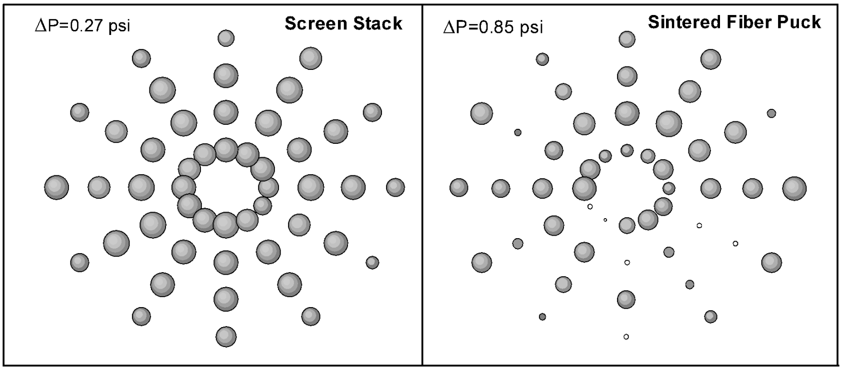

Figure 4. "Bubble graphs" of relative axial flow velocity through a representative screen-stack flow straightener and a representative sintered-random-fiber flow straightener, for a variety of radial and azimuthal positions. The bubbles diameters are proportional to flow velocity; the maximum flow velocity in both graphs is approximately 560 feet/sec.

CONCLUSIONS

Aircraft-carrier oxygen liquefaction represents a significant opportunity for acoustic-Stirling cooling technology. The requirements for the first LOX system for the Navy's new carrier class is an excellent fit for CFIC's largest acoustic drive; however, concerns about flow management in a large-diameter coldhead have motivated us to opt for a multihead, single drive design. Simulations suggest that the 55 gallon/day target should be achievable, even if the heads achieve only modest performance. However, reducing cost in production while maintaining performance may be a challenge.

REFERENCES

1. S.A. Potratz, T.D. Abbott, M.C. Johnson, and K.B. Albaugh, "Stirling-Type Pulse Tube Cryocooler with 1kW of Refrigeration at 77K," *Adv. in Cryogenic Engineering*, Vol. 53, Amer. Institute of Physics, Melville, NY (2008), pp. 42-48.

2. Zia, J., " A Pulse Tube Cryocooler with 300 W Refrigeration at 80 K and an Operating Efficiency of 19% Carnot," *Cryocoolers 14*, ICC Press, Boulder, CO (2007), pp. 141-148.