# Long Transfer Lines Enabling Large Separations between Compressor and Coldhead for High-Frequency Acoustic-Stirling ("Pulse-Tube") Coolers

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## ABSTRACT

One of the chief advantages of Joule-Thomson or Gifford- McMahon cooling systems over the more recently developed acoustic Stirling variety (e.g. high-frequency "pulse-tube" coolers) is the large separation distance between the compressor and coldhead. Long, flexible transfer lines typically connect the two components. This permits insertion of the coldhead into locations where the complete system would never fit, and isolates the coldhead from the vibrations of the compressor. High-frequency "split" Stirling and acoustic Stirling systems are not uncommon, but the separation distance is usually quite small, with a significant penalty on system efficiency. The usual approach has been to minimize the "dead volume" in the transfer line, making it relatively short and very small diameter. Recently, we have explored a different approach, using a fairly large transfer line diameter to lower the flow velocity (and hence the viscous loss), and increasing the length to over 1 meter, to allow these coolers to be used in the same applications as J-Ts and GMs. For small systems, this means using slightly larger compressor pistons to create the extra volume flow. The increase in compressor power required is small, because while there are losses in the transfer line, a long transfer line acts like an acoustic transformer, lowering the dynamic pressure at the compressor pistons for a given dynamic pressure at the coldhead. This lowers the seal loss in the compressor, which at least partially cancels the losses in the transfer line. In large systems, the increase in power is proportionally less, because the surface-to-volume ratio of the transfer lines is lower, and seal loss is a bigger fraction of the total input power. We will present simulations for various size systems, and data for one or two prototype systems, comparing capacity and efficiency with and without a long transfer line

## INTRODUCTION

One of the selling points of high-frequency acoustic-Stirling (or "pulse-tube") coolers over the Joule-Thomson (J-T) and Gifford-McMahon (GM) variety is their intrinsically higher thermal efficiency. At the same time, they have a slightly lower intrinsic thermal efficiency (at least at some scales) than displacer Stirling coolers, so every effort is made to maximize the efficiency of the acoustic Stirling, to reduce this competitive advantage of the displacer Stirling. However, as the prevalence of GM and J-T coolers attests, the most efficient device does not always win in the marketplace—it is the device that best fits the application in an overall sense, including first cost, convenience, and maintenance cost. Therefore, it may be worth considering configurations of the

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acoustic Stirling that increase its usefulness in key applications, even if they do not maximize its efficiency. One such configuration is to separate the coldhead from the compressor with a long transfer line. This certainly lowers the maximum achievable efficiency, but may allow the acoustic Stirling to access markets and applications previously served only by J-T and GM coolers. Furthermore, if optimizing such a configuration is approached as seriously as the optimization of regenerators and inertance tubes, the efficiency penalty associated with the long transfer line is less than one might suppose.

## ACOUSTIC-STIRLING WITH LONG TRANSFER LINE

### First Prototype

The interest in this configuration was spurred by a customer that wanted the acoustic-Stirling for its efficiency, but even more for its long life and absence of wearing parts and oil separators. At the same time, they needed the coldhead to be remotely located, for a cryopumping application where low vibration is especially important. "Remotely located" for them, however, does not mean 15 meters, but more like 1 meter—just enough to be able to locate the compressor on its own support, and reach the vacuum flange. After consulting with them, we chose 1.25 meters as the separation distance, which wound up being closer to 1.3 meters when the end connections of the transfer line were finalized.

This first "flexibly attached remote," or FAR, cooler prototype is shown in Figure 1, alongside our standard small cryocooler, the 2S102K. The 2S102K is rated for 8-10 watts at 77K, with 250 watts input; the FAR prototype achieves 10 watts at 77K with 330 watts input. The FAR system is certainly less efficient than the close-coupled 2S102K, but it still compares well with J-T or GM coolers. Table 1 shows a comparison of the 2S102K, the FAR, and one each of popular J-T and GM systems of similar cooling capacity.

The performance data are taken from the manufacturer's specifications. The FAR prototype, despite the long transfer line, is still more efficient than these alternatives.

**Figure 1**. Prototype split acoustic-Stirling system with remote coldhead, using a coldhead rated for 8-10 watts at 77K, driven by an oversize compressor designed for 20-25 watt coldheads, with a 1.3 meter, water-jacketed, 3/8 OD transfer line. The ¼" OD inertance tube is anchored to the transfer tube with tie-wraps. Our standard 2S102K close-coupled cooler, using the same head with a smaller compressor, is shown for comparison.

**Table 1**. Comparison of the 2S102K, the FAR, and popular J-T and GM systems of similar capacity.

| System | Cooling at 77K | Input power |
|---|---|---|
| 2S102K close coupled acoustic Stirling | 10 W | 250 W |
| Acoustic-Stirling FAR prototype | 10 W | 330 W |
| "CryoTiger" J-T cooler | 3.5 W | 500 W |
| Janis-SHI SRP 2620A G-M cooler | 10 W | 1900 W |

## Production Model

Although the FAR prototype is more efficient than the J-T or GM alternatives, it is not as efficient as it ought to be. This prototype was made without any particular effort to match the compressor to the combined load of the transfer line and coldhead—plus, the 'oversize' compressor was used (to allow this particular customer the option of 'overdriving' the 10-watt head in order to extend its capacity to ≥15 watts). A properly optimized system will be more efficient still. Although optimization of resonant systems tends to be iterative, the general approach to optimizing the efficiency of a remote acoustic Stirling system is: 1) choose the tube diameter that minimizes the transfer line losses for the desired separation distance, 2) choose the piston diameter so that when driving the combined load of transfer line and coldhead, the compressor motors achieve their ideal stroke (hence maximizing the motor efficiency), and 3) tune the moving mass of the motors as needed to achieve resonance at the operating frequency.

The results are not wholly intuitive if one's experience is limited to systems with all dimensions much smaller than a wavelength. The optimum transfer line is wider diameter than one might suppose; due to the turbulence in the transfer line, high velocity is worse than additional surface area, up to a point. A wider transfer line means more swept volume from the compressor, which requires larger pistons. The larger pistons don't increase the seal loss, however, because the pressure wave amplitude at the pistons is lower than before. In other words, the long transfer line acts like an "acoustic transformer," putting the pistons into a region of comparatively high volume flux and low pressure wave amplitude compared to the coldhead. Figure 2 illustrates the iconic standing waveforms of pressure and particle velocity. Figure 3 shows these waveforms as they apply to the acoustic field in the FAR prototype. The maximum in acoustic pressure is near the center of the

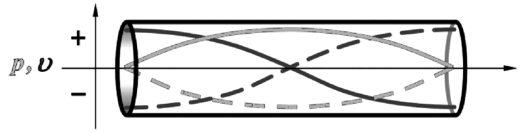

**Figure 2**. Standing wave in half-wave pipe, open at the ends. In the center of the pipe is a maximum in pressure wave amplitude and a minimum in particle velocity; the pressure is a minimum at the ends while the particle velocity is maximum.

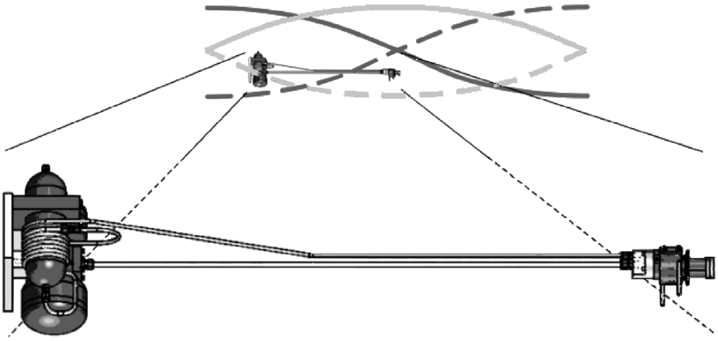

**Figure 3**. Standing waveforms of acoustic pressure and particle velocity superimposed on graphic of FAR system, showing how they apply to the acoustic field in the FAR prototype.

**Figure 4**. 2S102K-FAR production model; a pencil is shown for scale.

regenerator, so increasing the distance between the regenerator and the pistons decreases the acoustic pressure at the pistons. This, incidentally, may indicate that long transfer lines are less attractive in displacer Stirlings, because their typically larger pressure ratios imply larger standing-wave ratios, so a long transfer line would impose a much greater burden on the compressor, i.e., much more flow would be required to support the standing wave in the line as compared to the displacerless (acoustic) Stirling.

Figure 4 shows the production model designed using these principles. It uses flexible stainless hoses like those used in GM coolers, the large one being the transfer line and the smaller one being the inertance line. The black hoses are water lines (for cooling the warm end of the head). No data were available in time for this publication, but our simulations and past experience suggest this production model should achieve 10 W at 77K for 280 W input, or only 12% more input power than the close-coupled version.

## OTHER POSSIBLE REMOTE CONFIGURATIONS.

### Maximum Separation Distance

The production model shown in Figure 4 has a 1-meter transfer line. This is suitable for some applications, but it is reasonable to ask, what is the maximum separation distance achievable in a split acoustic-Stirling system? The transfer line losses are clearly higher than in systems where the gas undergoes low-velocity, steady flow in the lines; yet, if the starting efficiency is higher, one can tolerate some loss in the lines to achieve the same or better performance. From Figure 5, if we match the CryoTiger's 3.5 W at 77 K, for instance, then we can tolerate as much as 5 meters of separation between compressor and coldhead (which is greater than the 10 feet of separation that corresponds to the CryoTiger's 3.5 W performance point), while still drawing only 250 W.

### Performance at Larger Scales

As cooler size increases, surface-to-volume ratio decreases, and transfer line losses become less important. The seal loss reduction due to lower acoustic pressure at the pistons winds up obviating much of the transfer line loss, so the predicted efficiency is practically the same with and without the transfer line. Figure 6 shows how our 4 kW-input and 20-kW input coolers could be expected to perform with and without long transfer lines.

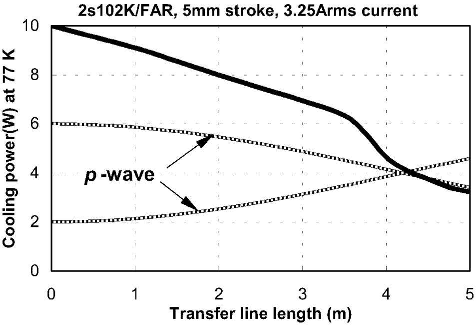

**Figure 5**. 2S102K-FAR cooling power as a function of transfer line length, while operating at constant stroke and current (the stroke and current that correspond to 250W input into a close-coupled coldhead). The input power is close to 250 W everywhere except near 4 m, where it dips due to the very low input impedance when the transfer line length corresponds to a quarter-wavelength. Note that the system is optimized for each length, which would not be necessary in a J-T system.

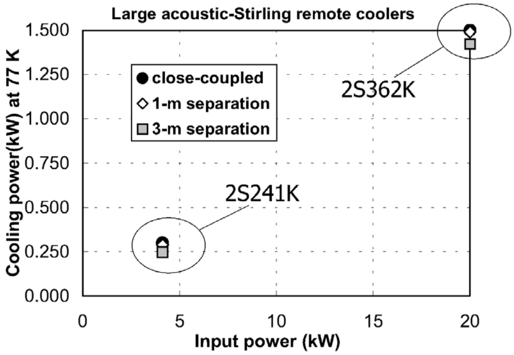

**Figure 6**. Effect, or lack of effect, on the performance of larger cryocoolers of long transfer lines.

## CONCLUSIONS

We may conclude that long transfer lines are indeed viable in acoustic-Stirling coolers, despite the higher losses that occur in these lines due to high-amplitude oscillating flow as compared to the slow DC flow in J-T and GM systems. The higher basic efficiency of the acoustic Stirling, and its other attractive features, makes it a serious alternative to existing remote cooling options. We can perhaps best illustrate this by a head-to-head comparison of various characteristics of the 2s102K-FAR production model versus the CryoTiger J-T system, shown in Figure 7.

The acoustic Stirling 'wins' in almost every category, except for first cost of single units (these, after all, are not yet in mass production) and in maximum separation distance. Of particular interest is the much shorter cooldown time for the acoustic Stirling remote cooler—unlike J-T coolers, the acoustic Stirling's capacity increases steadily with temperature, so even at comparable 77K performance, the acoustic Stirling has much larger capacity at higher temperatures.

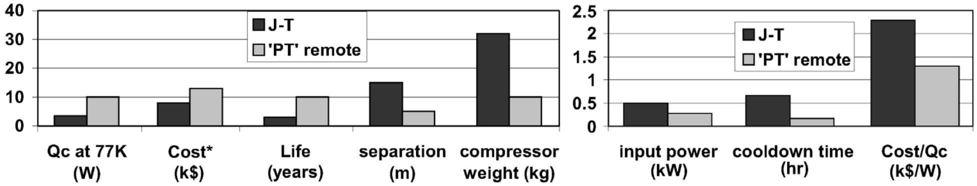

**Figure 7**. Comparison of some important features of the acoustic-Stirling ('PT') remote cooler and a popular J-T cooler.

These graphs do not tell the whole story, of course. There are other pros and cons of these systems to be considered. For instance, since the acoustic Stirling compressor contains no oil, it can be tilted or mounted any way one likes. On the other hand, the transfer line length cannot be changed arbitrarily between a compressor and coldhead that are optimized for one particular length, without incurring additional performance penalties. Also, the acoustic Stirling requires heat rejection at the head (there is no steady enthalpy flow to carry the “heat of compression” away, as in J-T or GM). Still, it is clear that an acoustic Stirling, or pulse-tube, cooler with a long transfer line should be useful for applications where efficiency, long life, and package size are desired and where especially long separation distances are not required.