

A New Load-Shifting Concept for Multistage Cryocoolers

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ABSTRACT

Single stage cryocoolers have been demonstrated to reach temperatures as low as ~20K without a load. To reach even lower temperatures or to have cooling at more than one temperature, multistage cryocoolers (MSCs) are often used. There are various types of MSCs, e.g., multistage Stirling, pulse tubes, Gifford-McMahon and reverse Brayton cryocoolers, etc. One of the disadvantages of multistage cryocoolers is known as load-shifting. For example, a two-stage cryocooler that is designed to operate between two temperatures has very little capability to shift the cooling load from one stage to another if the operating condition is different from that of the design point. This paper offers a new concept for multistage cryocoolers by connecting two different stages of the MSC with a tube / orifice or an inertance tube as potential phase shifting devices. Using a two-stage Stirling cryocooler as an example, these phase shift devices have been found to provide far bigger load shifting capability than the basic two-stage Stirling cryocooler. This new concept also helps to increase the cooling capacity at each stage (as much as 30% on the second stage at 35K in the current study).

INTRODUCTION

There are a number of multistage cryocoolers in the literature, ranging from Stirling^{1,2} to pulse tubes,³⁻⁵ to reverse Brayton cycles⁶. A common disadvantage of the MSCs is the limited ability to shift loads when operated in a different condition than the design point of the cryocooler, e.g., during ground testing. With the capability of tuning the displacer stroke and the phase angle (between the compressor and the displacer) the Stirling cryocooler appears to have an advantage over pulse tubes, as far as load shifting is concerned. Raytheon came up with the concept of a hybrid cryocooler^{7,8} with a first stage Stirling cryocooler and a second stage pulse tube, emphasizing the capability of load shifting. In the hybrid cryocooler, the first stage cooling is controlled by the Stirling displacer stroke and the phase angle between the compressor and the displacer, while the second stage cooling is controlled by the orifice between the second-stage pulse tube and the surge volume.

Due to the synchronized motion of the regenerators and the finite pressure drop, it is close to impossible to independently optimize the phase angle between the pressure and mass flow for maximum cooling in each stage of a multistage cryocooler. In the current paper, two phase shift

devices are proposed each between different stages of the cryocooler to optimize the phase angle at each stage. Figures 1a to 1c show the phase shift device between the first and second stages of three types of two-stage cryocoolers⁹.

DISCUSSION

A New Concept on Multistage Cryocooler

The effect of this new concept has been studied using a two stage Stirling cryocooler simulation, although this approach can also be used for other cryocoolers mentioned above. The study was performed using the SAGE software,¹⁰ which has been found to give excellent correlation to test data. A two-stage Stirling cooler model designed to produce 0.4W of cooling capacity at 35K and 2.5 W of cooling at 80K was used in this study. The dimensions of the cooler were optimized using the SAGE software and are listed in Table 1. Operating conditions of the cooler are summarized in Table 2

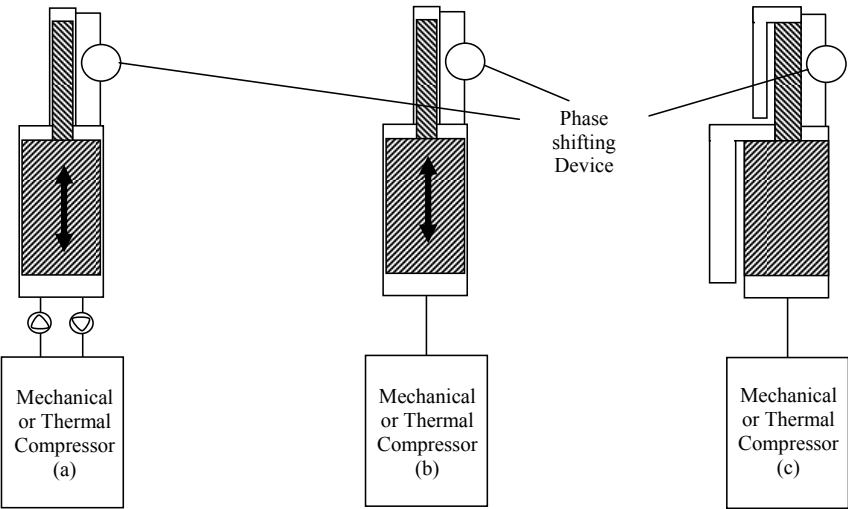


Figure 1. Two-Stage Cryocoolers, a) Gifford-McMahon, b) Stirling, c) Pulse Tube.

Table 1. Some important dimensions of the two-stage Stirling Cryocooler

	Component	Dimension / Material
Compressor	Piston Area	1 cm ²
	Maximum Stroke	1.64 cm
First Regenerator	Length	5.57 cm
	Diameter	1.32 cm
	Material	Stainless Steel Mesh
Second Regenerator	Length	4.19 cm
	Diameter	1.02 cm
	Material	Stainless Steel Mesh

Table 2. Operation conditions

Input PV Power	40 W
Frequency	45 Hz
Fill Pressure	3.4 MPa
Rejection Temperature	300 K

First Stage Phase shifting

Figure 2 shows the performance of the basic two-stage cryocooler with dimensions listed in Table 1 and operating conditions in Table 2. The first stage cooling capacity of the cooler is plotted as a function of the first stage temperature for various second stage cooling capacities at 35K. Since the cooler was optimized for 35K (second stage) and 80K (first stage), operating the first stage at temperatures below 80K results in a sharp drop of cooling capacity. Due to the lack of load shifting mechanism in a basic two stage Stirling cooler, the first stage cooling capacity is proportional to that of the second stage. For example, for the same first stage temperature, the second stage cooling capacity decreases as the first stage cooling capacity decreases accordingly.

Figure 3 shows the results of installing a phase shift device comprised of a capillary tube and an orifice between the first and second expansion spaces as shown in Figure 1b, with the orifice next to the second stage expansion space. Figure 4, on the other hand, summarizes the results using an inertance tube as the phase shifter. By including phase shifting devices, there is no sudden drop of the first stage cooling capacity as the first stage temperature is lowered because of a reduced coupling between the cooling capacities of the two expansion spaces. For each run, the displacer stroke, the phase angle and the orifice diameter / inertance value are optimized for best performance.

The first stage phase shifting performance of the orifice and inertance devices are compared to that of the basic two stage Stirling cryocooler in Figures 5 to 7, for three different second stage cooling capacities, 0.3 W, 0.4 W and 0.5 W respectively, at 35K. The orifice phase shifting device appears to provide better first stage cooling capacity at low first stage temperatures, while the inertance device provides better first stage cooling capacity at higher first stage temperatures.

Second Stage Phase shifting

In Figure 8, the second stage cooling capacity of a basic two stage Stirling cryocooler is plotted as a function of second stage temperature for various first stage cooling loads at 80K. By comparing Figure 9 to 8, one sees that the performance using an orifice device is very similar to that of a basic two-stage Stirling cryocooler, with a linear profile and the lowest temperature being around 25K (no load). The performance of the inertance phase shifting device (Figure 10) also results in a linear profile between the second stage cooling capacity and temperature, with the no load temperature at ~22K.

The second stage phase shifting performance of the orifice and inertance devices are compared to that of the basic two stage Stirling cryocooler in Figures 11 to 13, for three different first stage cooling capacities, 2.0 W, 2.5 W and 3.0 W respectively, at 80K. As pointed out earlier, the orifice phase shifting device does not appear to have much advantage over that of a basic two stage Stirling cryocooler. On the other hand, the inertance phase shift device results in close to 30% increase of cooling capacity compared to the basic two-stage Stirling cooler as shown in Figure 11. The orifice device has the disadvantage of irreversible losses associated with the mass flow, which is not present in the inertance tube. For each run, the displacer stroke, the phase angle and the orifice diameter / inertance value are optimized for best performance.

The phase shift devices proposed in this paper require controlling the mass flow across a flow resistance or through an inertance device. The former can be achieved through adjusting the opening of a valve. The adjusting of the inertance value (L/A) is slightly more complicated and will be discussed elsewhere.¹¹ The benefits of the phase shifting device conduction outweigh the enthalpy flow and conduction losses through the respective plumbing.

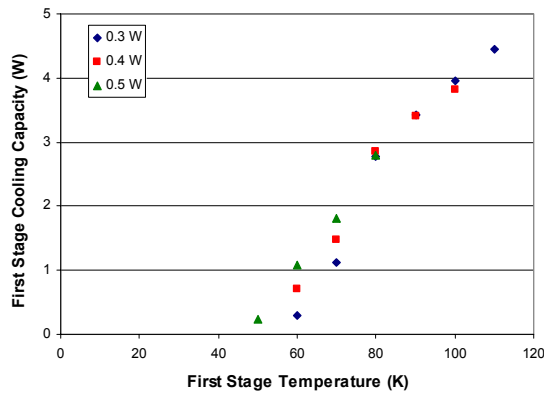


Figure 2. Basic two stage Stirling cryocooler- first stage cooling capacity as a function of first stage temperature with various second stage cooling capacities at 35K.

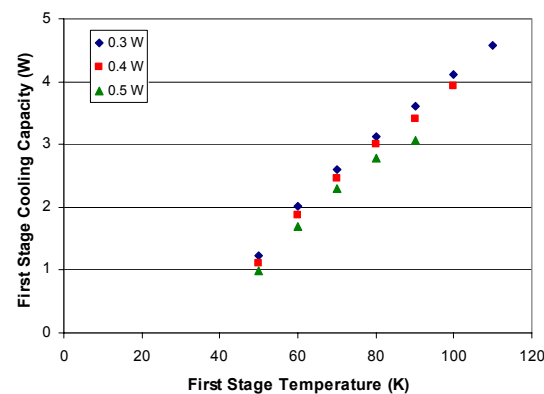


Figure 3. Two stage Stirling cryocooler with an orifice phase shift device- first stage cooling capacity as a function of first stage temperature with various second stage cooling capacities at 35K.

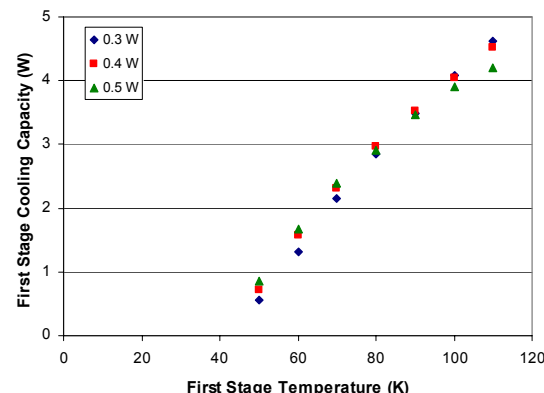


Figure 4. Two stage Stirling cryocooler with an inrtance phase shift device- first stage cooling capacity as a function of first stage temperature with various second stage cooling capacities at 35K.

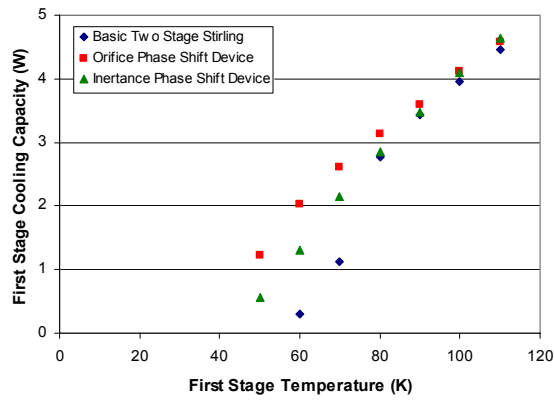


Figure 5. Comparison of phase shift devices- first stage cooling capacity as a function of first stage temperature, with 0.3 W second stage cooling capacity at 35 K.

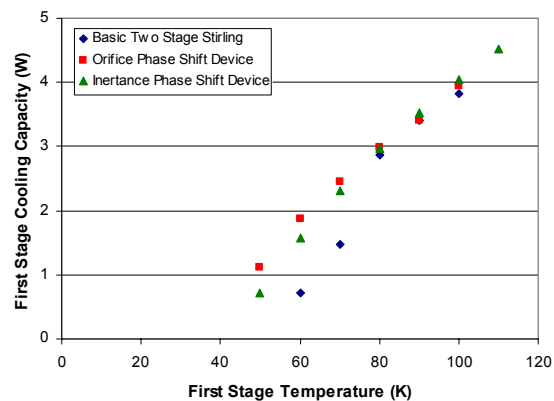


Figure 6. Comparison of phase shift devices- first stage cooling capacity as a function of first stage temperature, with 0.4 W second stage cooling capacity at 35 K.

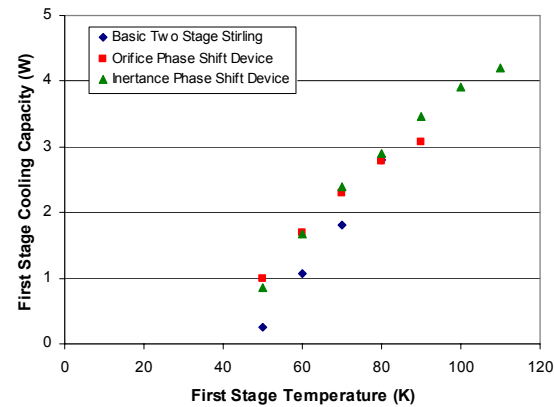


Figure 7. Comparison of phase shift devices- first stage cooling capacity as a function of first stage temperature, with 0.5 W second stage cooling capacity at 35 K.

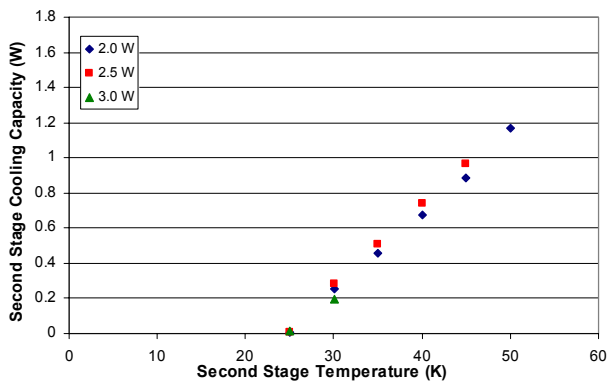


Figure 8. Basic two stage Stirling cryocooler- second stage cooling capacity as a function of second stage temperature, and various first stage cooling capacities at 80K .

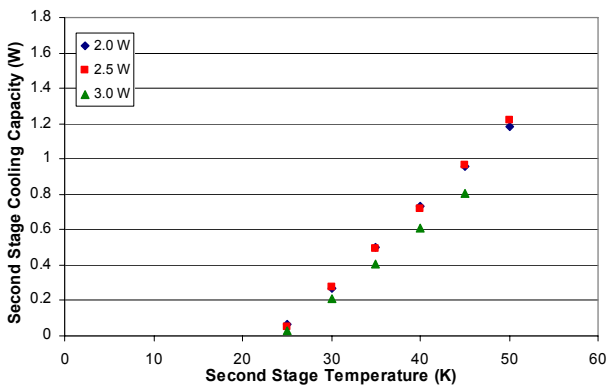


Figure 9. Two stage Stirling cryocooler with an orifice phase shift device- second stage cooling capacity as a function of second stage temperature, and various first stage cooling capacities at 80K.

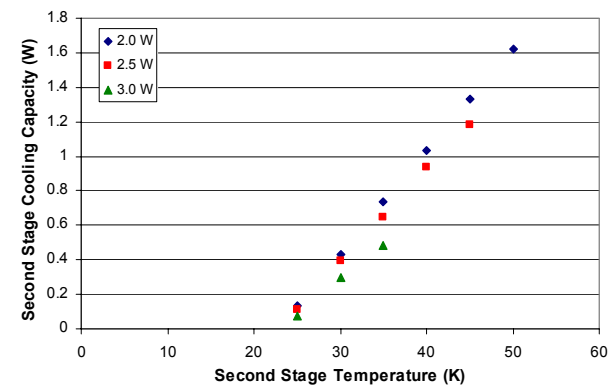


Figure 10. Two stage Stirling cryocooler with an inductance phase shift device- second stage cooling capacity as a function of second stage temperature, and various first stage cooling capacities at 80K.

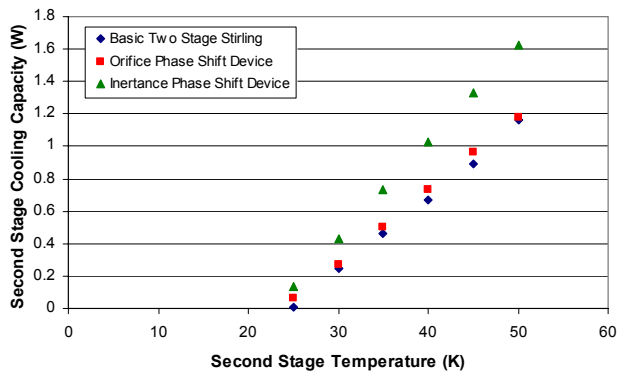


Figure 11. Comparison of phase shift devices- second stage cooling capacity as a function of second stage temperature, with 2.0 W first stage cooling capacities at 80K.

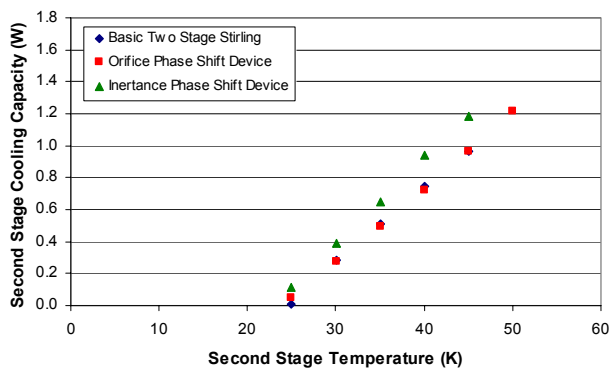


Figure 12. Comparison of phase shift devices- second stage cooling capacity as a function of second stage temperature, with 2.5 W first stage cooling capacities at 80K.

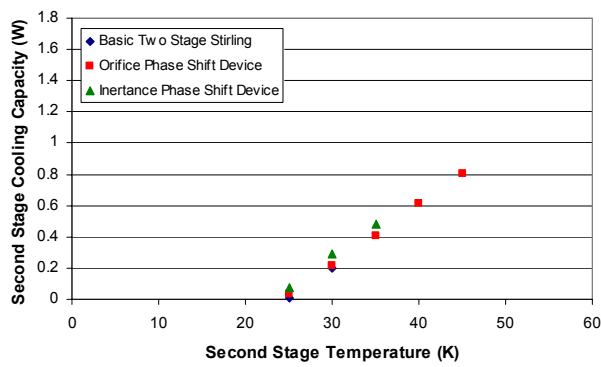


Figure 13. Comparison of phase shift devices- second stage cooling capacity as a function of second stage temperature, with 3.0 W first stage cooling capacities at 80K.

CONCLUSIONS

A new approach is proposed in this paper that can substantially improve the performance of a multistage cryocooler. The approach involves installing a phase-shifting device between different stages of the cryocooler, which helps to optimize the phase angle between the mass flow and pressure waves at each cooling stage. Using a two-stage Stirling cryocooler, two phase-shifting devices are studied in this paper, namely, a resistance device involving an orifice, and an inertance device. The resistance device appears to provide better cooling at the first stage, while the inertance device provides better cooling at the second stage. Both of these devices offer better load shifting capabilities compared to a basic two-stage Stirling cryocooler.

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