High-Capacity and Efficiency Stirling Cycle Cryocooler

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ABSTRACT

Infinia Technology Corporation (ITC) has successfully developed a low-cost, high-capacity Stirling cycle cryocooler to meet a number of 50K+ cryogenic system applications. The application of commercially available, low-cost, high-efficiency linear drive motors combined with ITC's proven long-life flexural bearing components, throughout the compressor portion of the system, has resulted in a compact, high-power (8+ kW electrical input) module that can be utilized for various cold head configurations. The modular nature of the drive allows the cold head assembly to be easily adapted to various cryogenic system requirements. As in the case of the drive system, ITC's flexure bearings are employed in the cold head displacer assembly. The resulting cryocooler assembly is compact, low mass, has low vibration characteristics, very quiet during operation, and employs an integrated power supply/controller ensuring safe operation. Testing has been carried out over a wide range of cold head operating conditions with an emphasis on conditions supporting the use of high-temperature superconductors, liquid oxygen/nitrogen production, as well as LNG production and LNG storage tank boil-off prevention. The cryocooler performance responds well with demonstrated efficiencies of up to 30+% of Carnot based on net useful cooling capacity and net electrical power to the cryocooler drive motors, at temperatures of 60K and above, even with non-optimized cold head configurations. Increased power level (16+ kW) compressor drive modules and multistage cold heads, are under active investigation at ITC. Low temperature refrigeration systems at conditions above the conventionally defined cryogenic arena are under active development as well.

INTRODUCTION

In recent years there has been an increasing interest in the application of cryogenic and other low-temperature cooling systems to applications where the combination of the market constraints and specific end user requirements are dramatically different than the classical requirements placed on cryo-refrigeration systems in the past.

Infinia Technology Corporation (ITC) has been actively developing a large, single-stage, high-capacity cryocooler focused on meeting potential emerging market requirements. This system makes extensive use of Stirling engine and cryocooler developments along with component technologies that have occurred over the past 10+ years at ITC and Infinia Corporation (now Qnergy, Inc.). Due to various potential market requirements the basic cryocooler, see Figure 1, was designed from the start to be quite modular in nature, allowing a

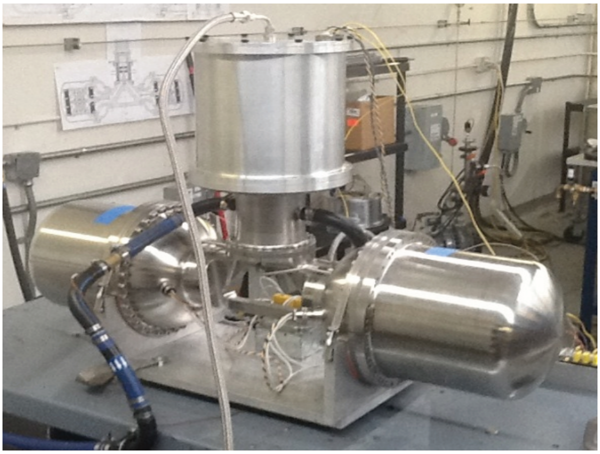

Figure 1. Cryocooler System

wide variation in the potential applications without requiring dramatic changes in the fundamental high-power linear drive. The unit as shown can utilize up to 8 kW of electrical input power, depending on the specific operating conditions, and has an overall length of 1,000 mm, height of 530 mm (without insulation package), a depth of 300 mm, and a total mass of 160 kg excluding the power supply/controller. The unit employs a configuration of two opposed linear drive pressure wave generators which provides for cancelation of essentially all of the drive motor vibration. The remaining net vibration on the cryocooler produced by the displacer motion is very small. The cryocooler is nominally rated by ITC at 650 W net cooling capacity at 77 K with 5,800 W of electrical power applied to the system, but is capable of operation over a wide range of temperatures. The variant currently being supplied to the US NAVY [1] is rated at 300 W of cooling at a nominal cold end temperature of 50 K. The current unit's net cooling capacity can also be modulated to follow cooling loads over the range of 20 to 100% of design at a specific operating temperature, and employs a "single button" start power supply controller incorporating a number of safety functions. Mean charge pressure is 42 Bar and operating speed is 60 Hz. In a final product configuration, the modular cold end assembly, made up of the displacer assembly, rejecter, regenerator, accepter (cold head) heat exchangers, would be optimized for the specific operating requirements; i.e., cooling capacity and operating temperature. The physical size, performance, and operating characteristics of the ITC system differ from other larger capacity coolers [2,3].

As in the case for all of ITC's cooler hardware designs over the past 25 years, Gedeon Associates' SAGE (or its earlier variants) Stirling cycle simulation model has been used exclusively with very good correlations between simulated and actual hardware test results.

GENERAL DESIGN PHILOSOPHY

The following sections provide an overview of the key factors that were considered in the configuration selection and operating characteristics of the current cryocooler system along with unique technical issues encountered in the unit's design. The discussion focuses both on the design decision-making process and key component technical issues. Test data will be noted throughout this discussion.

Pressure Wave Generators

The advent of low-cost high-efficiency linear drive motors has opened a number of market options for cryogenic or other low-temperature refrigeration systems. However, to fully exploit these advantages it is necessary to utilize these motors in a fully integrated pressure wave

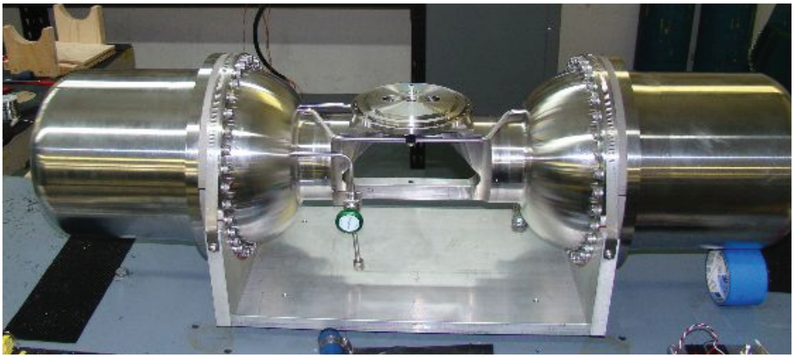

Figure 2. Pressure Wave Generator Module

generator module which meets the necessary performance and reliability requirements. To carry this out, ITC employs proven flexure bearings to provide the gas clearance seals while eliminating wear as a degradation mechanism. Combined with the use of low-cost manufacturing techniques, the resulting pressure wave generator package, shown in Figure 2, is quite compact relative to its 8-kW electric input power capability and has a power conversion efficiency (defined as Stirling cycle piston PV power/electrical power to the drive motor) >87%.

High Speed Orientation

A fundamental feature of all linear drive motors is that their physical size and quantity of materials employed to manufacture them is a strong function of the operating frequency of the device. For cost minimization purposes, this implies operation at as high a frequency as possible. For the current cryocooler, the drive motors are derived directly from Stirling engine systems operating at 60 Hz, thus defining the operating frequency of the unit. Due to the physical size and configuration of this class of cryocooler, the use of the high operating speed places a number of constraints on the mechanical configuration of the displacer assembly and the interface between the cold end accepter heat exchanger and the regenerator. Without careful design and mechanical implementation of this critical interface area, the performance (cooling capacity) can be dramatically degraded.

Pulse Tube vs. Stirling Cycle

Since the power piston assembly, flexural bearings, and other key components of the linear drive pressure wave generator are fundamentally the same for both the Pulse Tube and Stirling cycle, any decision process involving the selection of the cryocooler basic configuration (Pulse Tube vs. Stirling cycle) must be based on other factors. Specific issues of key importance for the current cryocooler system were component cost, reliability, and overall cost of operation. The latter becomes an important factor for the proposed system due to the fact that the operating costs (electrical power) for continuously run units of the type under consideration greatly exceeds the unit first costs over its design life. Figure 3 depicts a comparison of fundamental Stirling cycle and Pulse Tube performance as a function of the effective cold end temperature. For the range of temperatures of particular interest in the current hardware development effort (60 to 110K), the relative performance advantages are between 20 and 50%. When potential other market areas for derivatives of the current concept are considered, with required effective cold end operating temperatures of 175K (-100 C) and above, the performance advantages of the Stirling cycle configuration grow dramatically.

Countering these significant performance advantages, another key factor in the assessment of the Pulse Tube vs. Conventional Stirling cycle configuration is the potential additional complexity, reliability, and cost aspects of the displacer assembly present in the Stirling

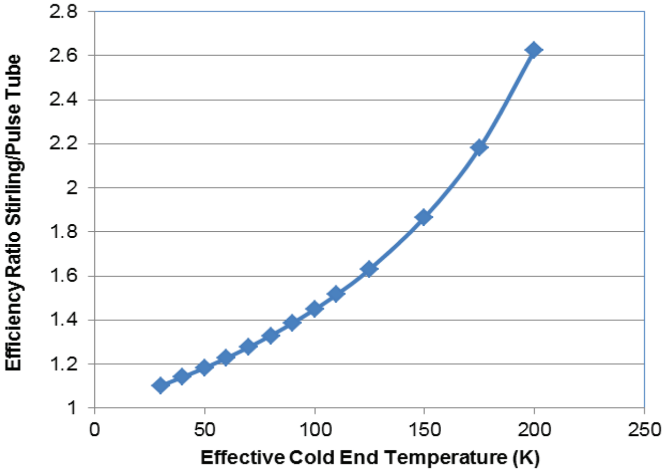

Figure 3. Pressure Wave Generator Module

configuration. Flexural-bearing-based displacer assembly failures are extremely rare. ITC experience shows a much lower failure rate for displacer assemblies than for the flexure bearing linear drive motor/power piston assemblies which are common to both Pulse Tube and Stirling systems. In addition, at the physical sizes and operating conditions of the cryocoolers under consideration, it is possible to directly employ flexural bearing configurations/designs that are in a mass production, with >500 units produced, and have proven high reliability based on cumulative operating times measured in the hundreds of million hours and very similar hardware with continuous operating times in excess of 100,000 hours. In the area of displacer assembly and cost, automated assembly processes have been developed that dramatically reduce the time for accurate, and highly repeatable, alignment of the displacer assembly. The key component of the displacer assembly, the flexures, have reached a point in their manufacturing evolution that the final flexure product is quite low in cost and driven primarily by the flexure raw material costs.

The review of the above factors clearly indicated that any additional cost of the displacer assembly was more than made up for in the reduction of the drive motor size requirements and costs due to the improved efficiency of the Stirling cycle configuration. In addition, based on extensive actual hardware experience, it was felt that the reliability of the current displacer/flexure bearing configuration was so high to essentially add no additional risk to system reliability over that already imposed by the flexure bearing based linear drive system.

ITC CRYOCOOLER FEATURES

Cooling Capacity

Figure 4, depicts the relative cooling capacity and input power required for the cryocooler over a range of cold head operating temperatures. At cold head temperatures above the nominally rated operating point, 77K, 650 W cooling and 5,800 W electrical input, the system becomes input power limited due to the fact that the displacer amplitude limit is reached. While the cooling capacity continues to climb significantly at warmer temperatures, this displacer constraint limits net cooling capacity. Via simple changes to the dynamic tuning of the displacer assembly [3] this effect can be to some degree minimized at operating temperatures up to about 90K, increasing net cooling capacity. To fully utilize the unit’s input power capabilities at high temperatures would require a displacer design change that results in a combination of increased displacer amplitude and /or displacer frontal area. The modular nature of the current cryocooler was specifically selected to allow such changes to be carried in a rapid and cost-effective manner.

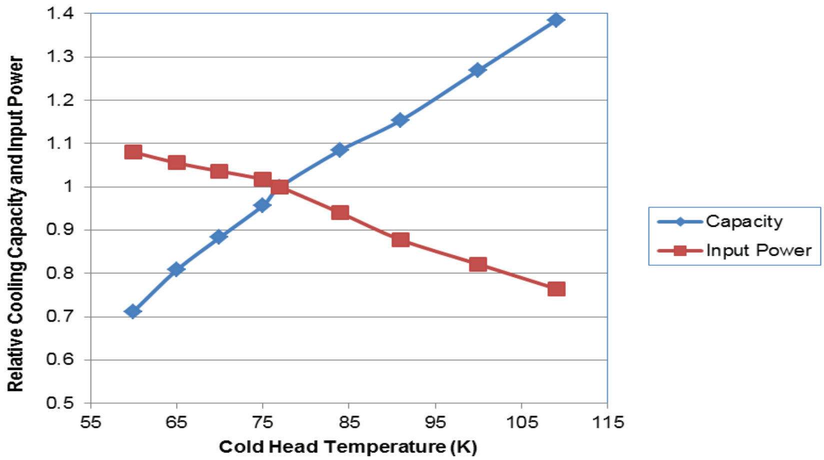

Figure 4. Cooling Capacity and Input Power vs. Cold Head Temperature

At all cold head temperatures under consideration, ensuring the proper integration of the interface between the cold head heat exchanger and the cold end of the regenerator assembly, is critical to maintain high performance. The combination of the cryocooler's high operating frequency (60 Hz), charge pressure of 42 Bar, and gas flow rates due to the high cycle input power, can result in local regenerator flow maldistributions which can have a dramatic effect on the cooling capacity due to ineffective use of the regenerator matrix [4,5,6]. The majority of these potential degradation mechanisms are present in a very small portion of the regenerator (<5 mm) adjacent to the cold heat exchanger entrance and involve a complex interaction of the flow jetting from the heat exchanger in one direction and flow from the regenerator into the heat exchanger in the other. The majority of these complex and interacting effects cannot be accurately modeled even with high-performance analytical tools. It is interesting to note that once these effects were resolved, the measured performance and operating characteristics of the cryocooler (cooling capacity, pressure amplitudes and phase angles, etc.) tracked quite well the projections of the SAGE cycle simulation model.

Waste Heat Rejections

A critical aspect of cryocooler systems employed in potential future market applications that must be carefully considered in the design process is the fact that in many cases they will have to move out of the laboratory environment into a much more rigorous set of ambient conditions. This would require the use of an independent waste heat rejection system with the ambient air being the final heat sink. By definition this implies a coolant (warm end) temperature above air ambient conditions which can have a significant impact on cryocooler performance. For example, Figure 5 depicts the measured relative changes in net cooling capacity, in input power required to maintain a fixed specific cold end temperature, and cryocooler efficiency as a function of the coolant inlet temperature based on actual hardware test values.

These effects imply that great care be taken in ensuring that the waste heat rejection system, which includes the Stirling cycle rejecter heat exchanger, air side heat exchanger, coolant circulating pump, and cooling fan must be optimized as an integrated system to ensure the required cooling capacity is available under worst-case operating conditions without excessive degradation on the overall cryocooler system performance [7]. For the current cryocooler, this heat rejection system would be based on a variant of the systems employed on the Qnergy, Inc. commercial systems due to good thermal performance characteristics under the unique combination of Stirling cycle operating conditions, high unit reliability, and low cost.

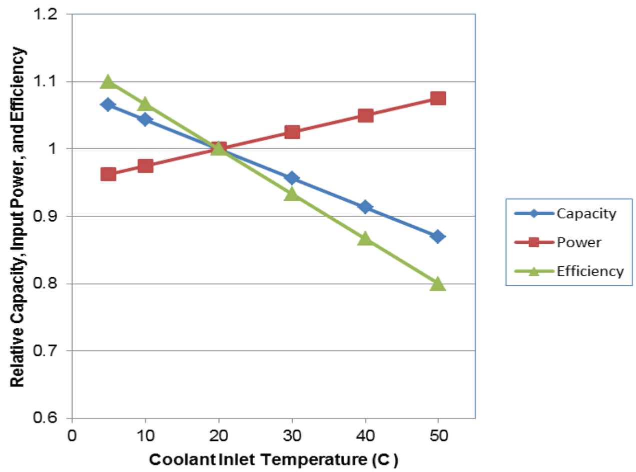

Figure 5. Impact of Heat Rejection Coolant Temperature of Cryocooler Performance

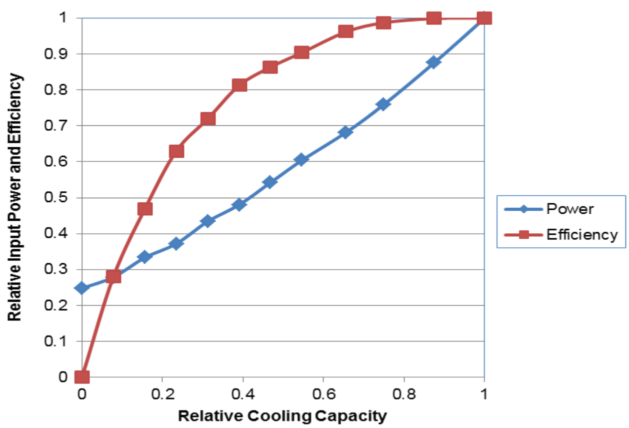

Figure 6. Cryocooler Capacity Modulation Characteristics (fixed cold head temperature)

Capacity Modulation

For many applications there are significant advantages to incorporating cooling capacity modulation/load following capability into the cryocooler system to minimize total electrical power consumption. Figure 6 depicts cryocooler test data indicating the variation in electrical input power and cryocooler efficiency as a function of the relative cooling capacity at a fixed cold head temperature within the unit's nominal operating range. With proper component design and cryocooler component integration, it is possible to retain quite good cryocooler efficiency (>80% of design) at cooling capacities of 40% of design and greater than 60% of design down to 20% of nominal cooling capacity.

Electrical Power Supply Issues

An important aspect to be considered in the use of the conventional free-piston Stirling cycle cryocoolers at the power levels under consideration is the fact that the linear drive motor is restricted to a single-phase electrical power supply of essentially constant frequency with variable applied voltage as the controlling mechanism. While this has not proven to be any problem in smaller cryocoolers of the free piston type, this constraint becomes more of an issue when power levels in the range utilized in the current ITC cryocooler (up to about 8 kWe), and

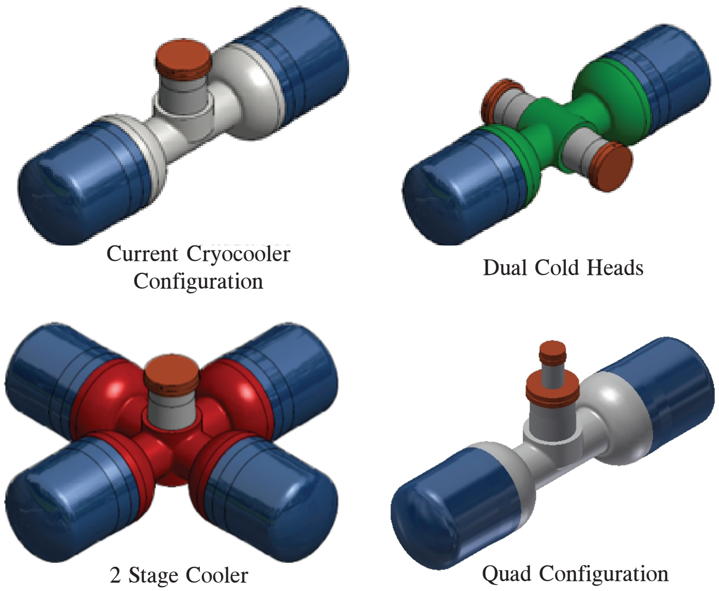

Figure 7. Cryocooler Configurations- Evolution/Development Efforts

clearly an important factor at power levels (>30 kWe) currently under active consideration by ITC. These factors can have a significant impact on the cost and efficiency of the power conditioning and controller features that must be employed to ensure full compatibility of the cryocooler with the electrical power supply, in particular for situations where the system must be incorporated into a 3-phase power supply. The ITC developed power conversion and control electronics can be easily configured for either 50 or 60 Hz primary power supplies.

Follow-On Development Efforts

Due to the previously discussed modular nature of the current ITC cryocooler, it is a relatively straightforward process to incorporate cold head configurations tailored to specific user requirements (cooling capacity/ temperature). Figure 7 depicts a number of cryocooler (or low-temperature refrigeration) systems under active investigation/development which evolved from the fundamental configuration of the current cryocooler. All of the variants employ the standard 4-kW pressure wave generator module in a paired manner, which provides full balancing of the drive system. The two-stage configuration provides a straightforward and efficient path to lower cold head conditions, supporting efforts involving superconductor applications in the 20 to 30 K range. Note that this cold head configuration is also applicable to any of the other configurations noted below. The dual cold head configuration provides full balancing of both the drive system and the displacers which can be an important advantage, as the displacer assemblies become considerably larger and more massive at cold end temperatures in the area of conventional "low temperature" refrigeration system applications. Another option is to employ four drive modules (Quad) with either single or dual cold heads to further increase net cooling capacity. Current linear drive motor developments are expected to yield a doubling of the current drive motor input power to 8 kW from the current 4 kW. All of the attributes of the current drives are retained and costs on a $/kW basis are expected to be at or below those of the current hardware. This will allow some of above configurations currently under active development by ITC to have input power levels in excess of 30 KW.

CONCLUSIONS

Infinia Technology Corporation (ITC) has successfully developed a low-cost, high-capacity Stirling cycle cryocooler to meet potential 50K+ cryogenic system applications. The application of commercially available, low-cost, high-efficiency linear drive motors and proven long-life, flexural bearing components throughout the compressor portion of the system has resulted in a compact, high-power pressure wave generator module that can be utilized for various cold head configurations. The use of proven flexural bearings and careful attention to the components making up the displacer assembly and associated Stirling cycle heat exchangers has provided both high system reliability and high thermal performance. The current cryocooler has been extensively tested over a wide range of conditions (50K to >120 K) with a nominal cooling capacity rating of 650 W at 77 K with an electrical input of only 5,800 W yielding a system performance of about 30% of Carnot. The modular design philosophy employed, along with the effective integration of all portions of the cryocooler and its supporting subsystems by ITC, allows for a number of alternative cryocooler systems configurations to be quickly and cost effectively developed in response to real market requirements.

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