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Cryocoolers: the state of the art and recent developments*

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Abstract

Cryocooler performance and reliability are continually improving. Consequently, they are more and more frequently implemented by physicists in their laboratory experiments or for commercial and space applications. The five kinds of cryocoolers most commonly used to provide cryogenic temperatures for various applications are the Joule–Thomson, Brayton, Stirling, Gifford–McMahon, and pulse tube cryocoolers. Many advances in all types have occurred in the past 20 years that have allowed all of them to be used for a wide variety of applications. The present state of the art and on-going developments of these cryocoolers are reviewed in this paper. In the past five years new research on these cryocoolers has offered the potential to significantly improve them and make them suitable for even more applications. The general trend of this new cryocooler research is also presented.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

A significant number of improvements to cryocoolers have occurred in the past 20 years, which in turn has allowed many more applications of cryogenics to flourish and find their way into the marketplace. Still, there are many attributes of cryocoolers that prevent many other applications of cryogenics from competing successfully with ambient temperature approaches. Although cryogenics can offer many benefits, as listed in table 1, the successful utilization of any benefit occurs only when that benefit outweighs the disadvantages associated with the cryocooler. These disadvantages or potential problems are listed in table 2. The major goal of cryocooler research is to reduce the impact of these disadvantages. For example, the use of cryocoolers for space applications did not occur in a major way until the reliability was improved to the point where a ten year lifetime could be achieved with a very high probability. The cost of cryocoolers has been a major factor hindering a more widespread use of cryocoolers in commercial applications. Cryocooler signatures, whether they are in the form of audible noise, vibration, or electromagnetic interference (EMI) also hinder the use of cryocoolers in many applications, especially those associated with sensitive electronics.

There are five common cryocooler types, each with different operating principles, but all rely on compression and expansion of a gas to bring about temperature changes. These different operating principles lead to certain advantages for some cryocooler types regarding potential problems, but disadvantages for other potential problems. Thus, each application may have one or two preferred cryocooler types that provide a better match for the application requirements. In this review only the gas cycles are considered, because they are used in almost all commercial and space cryocoolers for temperatures above 2 K. A more detailed review of cryocoolers was given recently by the author [1]. For temperatures below 1 K, both adiabatic demagnetization refrigerators (ADRs) and dilution refrigerators (DRs) have advanced to the point where commercial systems are now available, and both ADRs and DRs are being developed for space applications to cool detectors to temperatures of about 50 mK. Until the last few years, liquid helium was always used to precool these millikelvin refrigerators. However, the cost of liquid helium has increased rapidly in the last few years, so cryogen-free systems (dry systems) have been developed and made commercially available in the last couple of years that use 4 K pulse tube cryocoolers for the precooling. The first commercial 4 K pulse tube cryocoolers were made available in 1999, and the first DR precooled with a pulse tube cryocooler was described by Uhlig in 2002 [2]. Several commercial versions of

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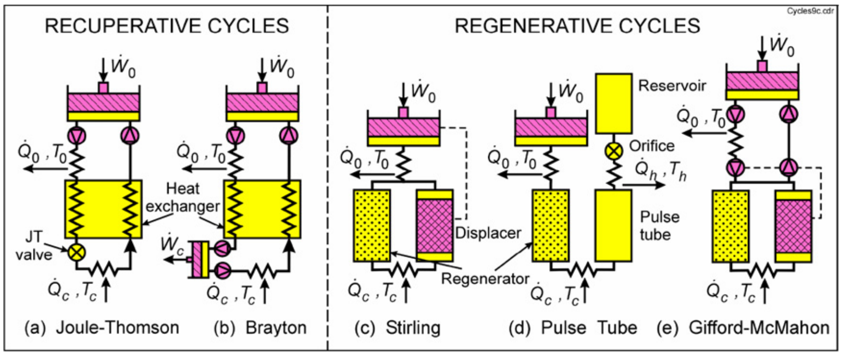

(a) Joule-Thomson (b) Brayton (c) Stirling (d) Pulse Tube (e) Gifford-McMahon

Figure 1. Schematics of five common types of cryocoolers.

Table 1. Benefits of cryogenic temperatures.

- Preservation of biological material and food
- Densification (liquefaction and separation)
- Quantum effects (superfluidity and superconductivity)
- Low thermal noise
- Low vapor pressure (cryopumping)
- Property changes (temporary and permanent)
- Tissue ablation (cryosurgery)

Table 2. Potential problems with cryocoolers.

- Reliability
- Efficiency
- Size and weight
- Cooldown time
- Vibration
- Electromagnetic interference (EMI)
- Heat rejection
- Cost

cryogen-free DRs and ADRs are now available, but this review does not cover developments of DRs and ADRs.

2. Cryocooler types

Schematics of the five major types of cryocoolers are shown in figure 1. The Joule–Thomson (JT) and the Brayton cycles are classified as recuperative cycles, in which there is a steady flow of gas in one direction with steady low and high pressures in the appropriate locations. Compression occurs at ambient temperature T_0, with the heat of compression being dissipated to the ambient. Expansion occurs at the cold end at a temperature T_c, where the net refrigeration power $\dot{Q}_c$ is absorbed. The steady flow and steady pressure in these two types of cryocoolers means that temperature oscillation and vibration are inherently low, particularly if rotary compressors are used and turbine expanders are used for the Brayton cycle. With no cold moving parts in the Joule–Thomson cycle, it can be scaled easily to microsizes. High-effectiveness heat exchangers are required to reach cryogenic temperatures, because the adiabatic temperature changes associated with either constant enthalpy expansion in the Joule–Thomson cycle or the constant entropy expansion in the Brayton cycle are small compared with the temperature difference between ambient and cryogenic temperatures. Heat exchanger effectiveness must typically be at least 95% to provide any net refrigeration at cryogenic temperatures when high pressures are used that are easily obtained with commercial compressors. Achieving such high effectiveness in compact recuperative heat exchangers has been challenging. The steady high pressure in the recuperative cycles means that an adsorber can be placed in the high-pressure stream to remove all traces of oil from an oil-lubricated compressor before the gas is cooled to cryogenic temperatures, where oil would freeze and clog the system.

The three regenerative cycles shown in figure 1 operate with oscillating flows and oscillating pressures, analogous to AC electrical systems, and almost always use high-pressure helium as the working fluid. Frequencies vary from about 1 Hz for the Gifford–McMahon (GM) and some pulse tube cryocoolers to about 60 Hz for Stirling and some pulse tube cryocoolers. In these regenerative cryocoolers heating occurs as the pressure is increasing, and cooling occurs as the pressure is decreasing. The use of a displacer in the Stirling and GM cryocoolers moves most of the gas to the hot end during the compression process and to the cold end during the expansion process. In the pulse tube cryocooler oscillating flow through the warm-end orifice (or a long capillary called an inertance tube) moves the gas with a similar phase relationship as provided by a displacer, but without a moving part. Thus, the pulse tube cryocooler has an inherent potential to be more reliable and have less vibration than either the Stirling or GM cryocoolers. The use of valves in the GM cryocooler or with pulse tubes driven with a GM-type compressor and rotary valve (known as GM-type pulse tubes) reduces their efficiency compared with valveless compressors (or pressure oscillators) as used in the Stirling or Stirling-type pulse tubes. However, the use of valves in the compression process provides a region of steady high pressure where an adsorber can be used in conjunction with a commercial oil-lubricated compressor in order to achieve high reliability at relatively low cost. The regenerative heat exchanger (regenerator) used for these cycles has only one flow channel, which is filled with a porous matrix with high surface area and heat capacity (packed screens or spheres). Heat is transferred from the 'hot blow' to the 'cold blow' via the matrix, where the heat is stored for a half cycle in the heat capacity of the matrix. Such heat exchangers are simple to make and are less expensive than

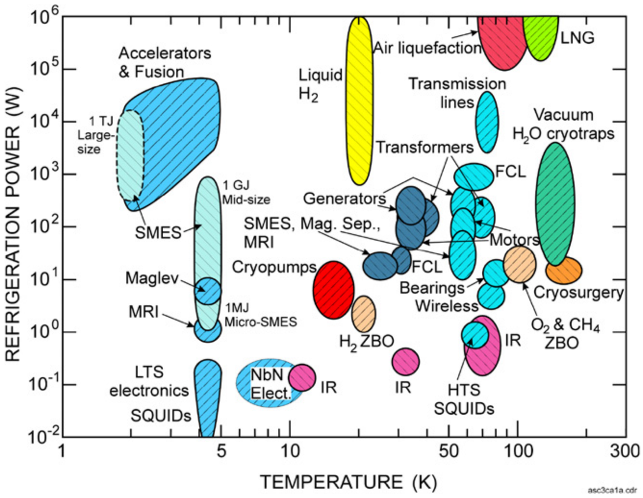

Figure 2. Map of cryocooler applications in plane of refrigeration power versus temperature.

recuperative heat exchangers, even though effectiveness values greater than about 95% are also required for the regenerative heat exchangers. For temperatures below about 10 K, heat capacities of regenerator matrix materials become rather low compared with that of helium gas, so the effectiveness of regenerators in this temperature range is limited.

3. Cryocooler applications

Figure 2 is a map of the major cryocooler applications in terms of the temperature and net refrigeration power required. The low vapor pressure of gases and vapors at cryogenic temperatures led to the development of commercial cryopumps in 1983. These employed a two-stage GM cryocooler to cool a charcoal adsorber to about 15 K. As many as 20 000 cryopumps per year have been produced during peak production years for use by the semiconductor industry in producing ultra clean vacuums. This application is the largest one for cryocoolers and resulted in the GM cryocooler becoming readily available from many manufacturers at relatively low cost and with high reliability between service periods of one or two years. The down time to replace the adsorber and displacer seals is only about one day.

The GM cryocooler also began to be used in 1985 for cooling the shields to 15 K for the superconducting magnets in magnetic resonance imaging (MRI) systems [3]. These magnets typically produce a magnetic field of 1.5 T, with some newer units providing fields of 3 T. Normal copper electromagnets are limited to fields of about 0.15 T, which makes them impossible to compete with superconductors. Over 22 000 MRI magnets are now in use since their first introduction in about 1980 [4]. With the development in 1990 of rare earth materials with high magnetic heat capacities in the range of 4–20 K [5], regenerators for GM cryocoolers could maintain high effectiveness down to 4 K. Thus, in 1995 4 K GM cryocoolers began to be used to recondense the boiloff liquid helium in MRI systems, and by 2003 there were more than 7000 of these 4 K coolers in use [6]. In some cases they are being used for direct conduction cooling of the magnet without the use of liquid helium, which allows for more compact systems. In most cases the existing commercial GM cryocoolers have been meeting the requirements for these two applications fairly well. As semiconductor feature size decreases and the spatial resolution of MRI improves, the vibration caused by the oscillating displacer of the GM cryocooler is becoming a more serious problem for cryopump and MRI applications. Some investigations of pulse tube cryocoolers for these applications have been undertaken, but so far they have not resulted in commercial hardware. The orientation dependence of the pulse tube cryocooler limits hardware designers and hinders its use for these applications.

Electric power applications using high-temperature superconducting (HTS) wires have been actively pursued for about the past ten years [7]. These applications include transmission lines, fault current limiters (FCL), transformers, motors, generators, and superconducting magnetic energy storage (SMES) magnets. The transmission lines require fairly large liquid nitrogen plants, but the other applications make use of intermediate-sized cryocoolers that deliver about 100 W of refrigeration power and require only a few kilowatts of input power. The GM cryocooler has been used for many laboratory studies of these applications, but Stirling-type pulse tube cryocoolers are under investigation for these applications because of their potential for higher efficiency and higher reliability. The scaling of pulse tube cryocoolers to these larger sizes has shown some problems with nonuniform flow that can reduce the efficiency. Solving this problem has become an active research area in the past few years.

The cooling of infrared sensors by the military to temperatures of about 80 K has been the largest application area for small cryocoolers. This application began around 1960 and was the first time cryocoolers were coupled directly to a device that needed cooling. Prior to that time liquid nitrogen or liquid helium, transported from the point of liquefaction, provided cooling at cryogenic temperatures, analogous to the use of ice for home refrigeration prior to the advent of the home refrigerator in the early 1900s. The first cryocoolers developed for this application were miniature JT cryocoolers operating in an open cycle from a small, high-pressure bottle of nitrogen or argon gas that was vented through the cooler to the atmosphere. These coolers were used for missile guidance and needed cooling for only a few minutes. By the mid 1960s, small Stirling cryocoolers were developed for cooling infrared sensors on military night vision equipment. By 1998 over 140 000 such coolers were produced for this application [8]. Typical refrigeration powers are in the range of 0.15–1.75 W. Initially, lifetimes were only a few hundred hours, but now lifetimes of at least 5000 h of continuous operation are common (one year ≈8800 h). For this application the need for higher reliability continues to increase. Other important requirements are low cost, low noise, small size, and low vibration.

The use of cooled infrared sensors in space is of particular interest to the military for surveillance activities and to space agencies for astronomy and earth-observing applications. Temperatures required for surveillance activities are mostly in the range of 10–150 K, where the lower temperatures are required for the detection of longer wavelengths. The infrared astronomy applications generally require temperatures in the range of 2 to about 100 K. Gamma-ray detectors of high-purity germanium require cooling to 90 K. Some x-ray and gamma-ray astronomy missions are planned that make use of very sensitive microbolometers made with transition-edge superconducting (TES) devices that have transition temperatures in the range of 50–100 mK. Such low temperatures can not be achieved with the gas cycles shown in figure 1. Other refrigeration techniques are being developed for these low temperatures, but they all must be precooled to temperatures of about 6 K or lower by use of the gas cycles. The development of cryocoolers for space applications began in earnest in the 1980s, and the first long-life cryocooler flew in space in 1991 [9]. The most important requirement of space cryocoolers is very high reliability. Lifetimes of 10 years are usually desired. Other important requirements include high efficiency and low mass. Cryocoolers qualified for space applications end up being very expensive, but the cost requirement is usually such that the cooler cost should be small compared to the overall mission cost. The development of cryocoolers for space applications has led to many significant advances in cryocooler reliability and efficiency.

Most electronic applications of superconductors need only miniature cryocoolers, primarily to absorb the small amount of heat being conducted through electrical leads from room temperature. For HTS applications, power inputs to drive the cryocooler may be in the range of a few watts to a hundred watts, but some new research is currently underway with microcryocoolers using MEMS fabrication techniques. Power inputs for such small coolers could be less than one watt, which is easily provided with small batteries. HTS microwave filters for cellular phone base stations require about 6 W of cooling at 77 K and are currently employed in about 4000 base stations, which is about 2% of the total number of US base stations. Low-temperature superconducting (LTS) electronics offer performance advantages over their HTS counterparts, but power inputs of about a kilowatt are required for these cryocoolers even to obtain 0.1 W of cooling. Current research on improved cryocoolers for temperatures around 4 K may lead to input powers being reduced to about 200 W within the next few years.

In the past ten years closed-cycle cryocoolers have been used for many cryosurgical applications. One application that was approved for general use in the US by the Food and Drug Administration is in the freezing of the uterine lining in women who have abnormal menstrual bleeding. A mixed refrigerant JT cryocooler has been developed for this application [10]. The cold tip of JT cryocoolers is easily miniaturized for use in cryogenic catheters of small diameter. JT cryocoolers greatly reduce the size of the overall system compared with that of liquid nitrogen systems. Because the cooling takes place after the gas expansion at the tip, it can be used in long catheters that can be inserted through veins to reach internal organs, such as the heart. Cryogenic catheters using the JT expansion of nitrous oxide are now being extensively studied for cryoablation of particular locations in the heart that cause heart arrhythmia. Thousands of clinical trials in the last two or three years have shown it to be very successful and much safer than radio frequency (RF) ablation [11]. Cryotherapy is also being used for the freezing of many types of cancers [12].

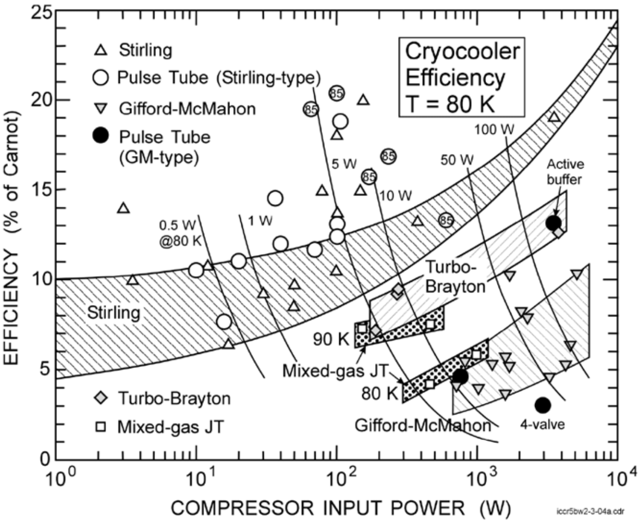

Figure 3. Efficiency of cryocoolers at about 80 K.

4. Cryocooler state of the art

Cryocooler research in the past 20 years has led to significant improvements in all the potential problem areas listed in table 2. Lifetimes of ten years are now possible in space cryocoolers, and five year lifetimes are possible in similar cryocoolers developed for commercial applications. Efficiencies at 80 K can be as high as about 20% of Carnot for some of the best space cryocoolers, whereas 10%–15% of Carnot is more typical of some of the best commercial cryocoolers. A comparison of cryocooler efficiencies near 80 K is given in figure 3. For lower temperatures the efficiency, even in terms of a fraction of Carnot, drops significantly, as shown in figure 4. At 4 K efficiencies of about 1% of Carnot or less are typical, except in large helium liquefaction plants, where efficiencies can be as high as 30% of Carnot. A recent survey of hundreds of mostly commercial cryocoolers with cooling powers less than several tens of watts provides data on reliability, efficiency, size, and mass of these cryocoolers [13]. The current status of the five cryocooler types is given in the following paragraphs.

4.1. Joule–Thomson cryocoolers

A major disadvantage of JT cryocoolers that use pure nitrogen or argon gas is the requirement of very high pressures to achieve even a modest efficiency. The JT expansion provides cooling only with real gases where the enthalpy is a function of pressure. Both pure nitrogen or argon at room temperature have only a small pressure dependence on the enthalpy, which causes the JT cooling effect to be small. The addition of higher boiling point components to nitrogen or argon increases the JT effect. Although the use of mixed refrigerants was proposed

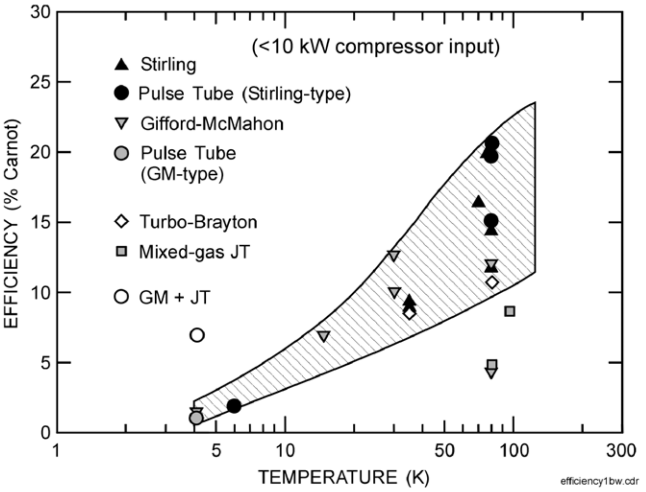

Figure 4. Efficiency of small cryocoolers as a function of cold end temperature.

as early as 1936 for the liquefaction of natural gas [14], it was not until the past 20 or 30 years that it has been used extensively. The use of mixed refrigerants in small JT coolers was first developed under classified programs in the Soviet Union in the 1970s and 1980s. Open development in other countries followed in the late 1980s [15]. The use of mixed refrigerants for temperatures down to about 80 K increases the efficiency in JT cryocoolers by an order of magnitude for high pressures of about 2.5 MPa, which can be obtained with commercial oil-lubricated refrigeration compressors. The use of these refrigeration compressors allows costs of these cryocoolers to be as low as about $3000. A small fractionating column is often used to return the lubricating oil mixed with the refrigerant to the compressor before it reaches the lowest temperature and freezes. These mixed refrigerant JT coolers (often called Kleemenko cryocoolers) have achieved lifetimes of about ten years [16]. Over 1000 of these coolers are now in the field for cooling gamma-ray detectors to about 90 K.

4.2. Brayton cryocoolers

The advantage of an expander at the cold end is the ability to extract work and provide gross refrigeration equal to that extracted work. The cooling occurs even in an ideal gas. However, the moving part at the cold end can lead to reliability problems. Most of the work on small Brayton cryocoolers in the past 20 or 30 years has involved turbine expanders and centrifugal compressors that spin at high speeds on gas bearings. The gas bearings eliminate rubbing contact and can provide the ten year lifetimes required for space applications. For small Brayton cryocoolers the challenge is fabricating miniature turboexpanders that maintain acceptable expansion efficiency. Turbine diameters of about 6 mm on shafts of 3 mm diameter spinning at 2000–5000 rev s^{-1} are typical in systems reviewed by McCormick *et al* [17] for use in space applications of cooled infrared sensors. Centrifugal compressors providing a pressure ratio of about 1.6 with a low-side pressure of 0.1 MPa are used with these systems. A similar system was installed on the Hubble Space Telescope in 2002 that provides 7.1 W of cooling at 70 K with 315 W of input power, for an efficiency of 7% of Carnot [18, 19]. The working fluid used in the turbo-Brayton cryocoolers is usually neon when operating above 35 K, with helium required for lower temperatures. The low-pressure ratio used in these turbo-Brayton cryocoolers leads to a refrigeration power per unit flow that is quite small. Thus, the heat exchanger must have a very high effectiveness, which causes it to be the largest component in the system. A two-stage turbo-Brayton cryocooler for temperatures down to 6 K with helium in the second stage was designed and underwent component testing at temperatures below 20 K [20]. However, the efficiency of the turbo-Brayton cryocooler is somewhat less than the Stirling and pulse tube cryocoolers. Research on improved heat exchangers with higher effectiveness using micromachined silicon is currently in progress that also promises to reduce the size of the heat exchanger [21].

4.3. Stirling cryocoolers

Stirling cryocoolers were first developed in the early 1950s for the liquefaction of air in small quantities in relatively remote locations. In the 1960s smaller Stirling cryocoolers were first used for the cooling of infrared detectors in military night vision equipment. These early coolers were rotary types with crank drives and rubbing piston rings. Lifetimes were only a few hundred hours, but with improved materials for the rubbing contacts, lifetimes of about one year are now possible. In the meantime, linearly-driven Stirling cryocoolers were introduced in the 1970s that eliminated most of the rubbing contact and offered longer lifetimes early in their development. Currently, their lifetimes are also around one year. By 1998 over 140 000 of the small Stirling cryocoolers had been produced for use in night vision equipment [8]. Refrigeration powers range from about 0.15 to 1.75 W at 80 K. Stirling cryocoolers were first developed seriously for space applications after the introduction of flexure bearings to support the piston and displacer inside the cylinder walls with no rubbing contact [22]. Lifetimes of at least 10 years is now expected of these coolers that have eliminated all rubbing contact. Often their lifetimes exceed that of the accompanying electronics. Gas-bearing support of the piston was an alternative approach for long lifetime introduced in the 1990s in some commercial applications for the cooling of superconducting microwave filters in mobile phone base stations [23].

4.4. Gifford–McMahon cryocoolers

Gifford–McMahon (GM) cryocoolers were first developed in 1960 [24]. They began to be used in the 1980s for the cooling of charcoal adsorbers to about 15 K in cryopumps. Their use in cryopumps in semiconductor fabrication equipment for producing very clean vacuums provided a large market for these cryocoolers and led to many improvements in their reliability and in the reduction of their costs. Maintenance intervals of one to two years are typical for these cryocoolers and are usually part of planned maintenance of the entire fabrication equipment. In the late 1980s the GM cryocooler also began to be used for the cooling of radiation shields in MRI equipment for reducing the boiloff rate of the liquid helium that was used to maintain the superconducting magnet at 4.2 K. The use in 1990 of regenerators made with rare earth materials with high heat capacities in the range of 4–20 K allowed the GM cryocooler to achieve temperatures of 4 K [5]. These new coolers could then eliminate the helium boiloff, and some compact MRI systems have been developed recently that use no liquid helium (cryogen-free systems). The commercial availability of the GM cryocoolers, both one- and two-stage systems, has led them to be used for many development projects involving new applications.

4.5. *Pulse tube cryocoolers*

With the introduction of the orifice in pulse tube refrigerators [25] and the subsequent relocation of the orifice [26] allowed them to achieve temperatures below 60 K in the mid 1980s. With the addition of the double inlet in 1990 [27] and the inertance tube in the mid 1990s [28–30] efficiencies of the pulse tube cryocooler, when driven with a valveless compressor (Stirling-type pulse tube) began to match, or in some cases even exceed, that of the Stirling cryocooler. Efficiencies around 20% of Carnot at 80 K have been achieved [31]. The high efficiency and the high reliability possible when driven with a flexure-bearing compressor has led to their use in many space applications. When the high heat capacity matrix materials are used in the coldest end of the regenerator, temperatures of 4 K have been achieved, first in 1 Hz GM-type pulse tubes, and more recently in 30 Hz Stirling-type pulse tubes [32]. Commercial 4 K pulse tube cryocoolers are of the GM type and are available in refrigeration powers that range from about 0.1 to 1.5 W at 4 K.

5. Recent developments

5.1. *Thermoacoustically driven pulse tubes*

In 1990 the first cryocooler with no moving parts was demonstrated when 90 K was achieved by use of a standing-wave thermoacoustic engine instead of a mechanical compressor to provide the oscillating pressure for a pulse tube cryocooler [33]. A heat source at about 600–700 °C provided the power input. With no moving parts, the reliability of such a cryocooler should be very high. The 10 m long resonant tube set the frequency at 27 Hz. The pressure ratio produced with the engine was only 1.10, compared with a ratio of about 1.3 for a mechanical driver. In 1999 Backhaus and Swift developed a traveling-wave thermoacoustic engine that had a higher efficiency than that of the standing-wave engine and was able to achieve a pressure ratio of about 1.2 [34]. This type of driver has then been used for most subsequent research on thermoacoustically driven pulse tubes. However, the lower-pressure ratio compared with that of a mechanically driven system made it difficult to achieve lower temperatures. In 2005 Dai *et al* [35] showed that by use of a properly tapered resonant tube, the pressure ratio could be increased to 1.26. With the driver coupled to a single-stage pulse tube cooler they achieved a low temperature of 68.8 K. Further improvements were made to the system by addition of an acoustic amplifier that allowed the thermoacoustic engine to operate with a lower-pressure ratio and achieve higher efficiencies while obtaining a pressure ratio of 1.27 at the pulse tube entrance. A flexible membrane included in the connection between the engine and the pulse tube allowed the use of nitrogen in the driver to reduce the frequency with helium still used in the pulse tube. When such a system was used to drive a two-stage pulse tube cryocooler, a low temperature of 18.7 K was achieved [36].

5.2. *Higher frequencies*

The acoustic or PV power delivered by a pressure oscillator (compressor) is proportional to the frequency for a given swept volume. By increasing the frequency the compressor can be made smaller for a given power. Because the dominant volume in Stirling and pulse tube cryocoolers is the compressor, a significant size reduction would be possible by use of higher frequencies. For several decades the highest frequency for regenerative cryocoolers has been about 60 Hz because of a significant loss of regenerator effectiveness at higher frequencies. In 2006 Radebaugh and O'Gallagher [37] showed from modeling that by increasing the pressure and reducing the hydraulic diameter of the regenerator matrix, high effectiveness could be maintained in regenerative cryocoolers up to about 1 kHz frequencies. To achieve the best performance, the models predicted that an average pressure of 7 MPa and a hydraulic diameter of 12 μm in screens were needed. The finest commercially available screen is 635 mesh, which has a wire diameter of 20.3 μm and a hydraulic diameter of 30.6 μm. Vanapalli *et al* [38] showed that with this screen and a pressure of 3.5 MPa, high efficiency could be maintained at 80 K in a pulse tube cryocooler operating at 120 Hz. A minimum temperature of 50 K was achieved. An added benefit of this higher frequency and higher power density in the cold finger was a shorter cooldown period of only 5.5 min to reach 80 K. If the mass of the heater and the large flanges were removed, a cooldown period of less than one minute would be possible [39]. Further progress on using higher frequencies relies on the development of regenerator geometries with smaller hydraulic diameters and compressors designed for resonant operation at higher frequencies. A low temperature of 70 K was achieved by Zhu *et al* [40] at 300 Hz and a pressure of 4.13 MPa with a thermoacoustically driven pulse tube cryocooler. With this high frequency the length of the resonant tube of the driver was only about 1.5 m instead of about 10 m for 30 Hz.

5.3. *Large pulse tube cryocoolers*

The rapidly growing interest in power applications of superconductors, small-scale industrial gas liquefaction, and zero-boiloff cryogenic containers for both terrestrial and space applications has brought about several research projects aimed at increasing the power of efficient pulse tube cryocoolers. Powers up to about 1 kW of refrigeration at 80 K are under investigation. Many researchers, including us, have found that in large pulse tube cryocoolers there is a strong tendency for a circulating streaming effect to develop in the pulse tube and the regenerator that manifests itself in low efficiency and an azimuthal temperature variation that may be as high as 150 K around the circumference of the regenerator and/or the pulse tube. The effect appears rather abruptly at some critical input power. The cause of the streaming in the regenerator appears to come from an inherent instability when there is poor thermal communication in the radial direction [41]. Dietrich *et al* [41] showed that addition of copper screens or plates along the length of the regenerator greatly reduced the temperature inhomogeneities and improved the efficiency. The minimum temperature achieved was reduced from 54 to 34 K with the increased radial thermal conduction. They achieved a cooling power of 200 W at 70 K with an electrical input power of 8.6 kW, for an efficiency of 7.6% of Carnot. The largest pulse tube cryocooler built to date provides 300 W of net refrigeration at 80 K with an operating efficiency of 19% of Carnot [42]. In the last two or three years several studies involving CFD modeling of the pulse tube or the complete cryocooler have begun, which offer the potential of sorting out further causes for nonuniform flows.

5.4. High efficiency cryocoolers for 4 K

The Carnot efficiency of cryocoolers drops significantly for temperatures down to about 4 K. Efficiencies of only 1% of Carnot are typical in this temperature range. Input powers of about 1 kW or more are required to achieve 100 mW of cooling at 4 K. Because a temperature of about 4 K is needed for low-temperature superconducting (LTS) electronic devices, there is a strong desire to increase the efficiency and, therefore, decrease the input power of 4 K cryocoolers. With less power required from the compressor the size of the system can be decreased to the point where a rack-mounted system is possible. The use of Stirling-type pulse tubes for this temperature offers the possibility of higher efficiencies because of the high efficiency in the compressor compared with the GM-type compressor, which uses valves. However, to keep the size of the Stirling-type compressor small, it must be operated at frequencies of about 30 Hz or more, which is also the frequency the regenerator will experience. Typically, it has been found difficult to achieve efficient regenerator operation at such high frequencies at 4 K. The causes of this poor regenerator performance are not fully understood at this time, but it is known that low matrix heat capacities and real-gas effects in the helium are partly responsible. Recently the use of ^{3}He in place of the ^{4}He in a 30 Hz pulse tube cryocooler has shown increased efficiency at 4 K [32]. Modeling studies [43] have shown that optimized regenerators using ^{3}He can have significantly improved performance, especially if the average pressure is reduced to about 0.5–1.0 MPa. Low-porosity matrix geometries in the high heat capacity materials can lead to further increases in the regenerator performance. Some efforts to provide such materials through the use of micromachined techniques are underway.

5.5. Cryogen-free (dry) 4 K cryostats

The rapidly increasing price of helium gas in the last few years and the interruptions in the supply of liquid to many laboratories has led to the development of many cryogen-free (dry) 4 K cryostats, which usually use commercial 4 K GM-type pulse tube cryocoolers to provide the necessary cooling. For experiments that are extremely sensitive to vibration, vibration isolation techniques can be employed to reduced the vibration amplitude at the sample to as low as 0.1 μm when cryogen-free cryostats are being used. Such techniques, as shown in figure 5, were used in a laser interferometer cryostat for the detection of gravity waves [44]. Without such techniques the vibration amplitude from the pulse tube cryocooler is about 10 μm peak to peak. In cases where a liquid helium bath is required to maintain a thermal reservoir for some experiments, a recondensing system employing a 4 K pulse tube cryocooler inserted in the neck of a special liquid helium dewar recondenses the helium boiled off before it warms up to room temperature, as illustrated in figure 6. An experimental probe can be inserted into the dewar through a second neck. A 1 watt pulse tube cryocooler used in one of these recondensing systems can recondense about 20 l/day, although 30 l/day would be the theoretical rate based on the heat of vaporization with no increase in the background heat leak. A helium recondensing system with two 4 K GM cryocoolers located outside a shielded room has been used to cool a magnetoencephalography (MEG) experiment inside the room via a transfer line [45]. The noise level for the SQUID sensor in the MEG system had an amplitude less than about 30 fT Hz$^{-1/2}$ in the range of 1–100 Hz, which is normal for these kinds of SQUIDs. Cryogen-free superconducting magnet systems are now commercially available, including one with fields to 17 T.

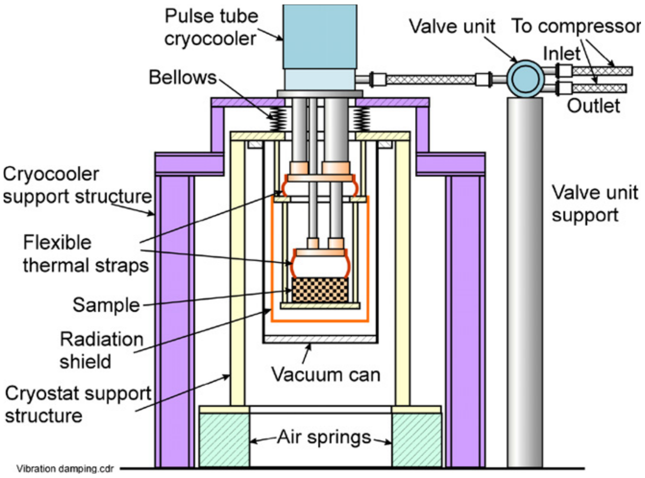

Figure 5. Cryocooler vibration damping scheme capable of achieving 0.1 μm vibration amplitudes.

5.6. Microcryocoolers

Many electronic sensors experience an enhanced sensitivity at lower temperatures. With the advent of MicroElectroMechanical Systems (MEMS) fabrication techniques, many of these sensors are being greatly reduced in size and in power requirements. As these devices are reduced in size, the demand for

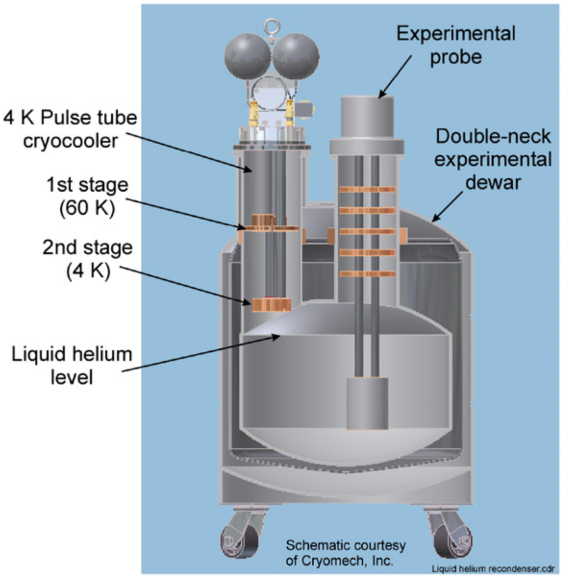

Figure 6. Liquid helium recondenser in double-neck dewar.

a similarly sized cryocooler is steadily increasing. A miniature JT cryocooler was developed many years ago to operate from a compressed gas cylinder. The cold finger was made with glass slides, which had the flow channels etched in the glass [46]. Until the last few years nothing on the level of a MEMS-scale cold finger had been attempted. Now several research groups are working on such systems. One of the earlier and thorough studies of a microcryocooler was reported in 2006 by Lerou *et al* [47]. They developed an adsorption compressor for use with the cold finger. The heat exchanger of the cold finger consisted of glass sheets 175 μm thick bonded together to form a parallel plate heat exchanger with dimensions of 30 mm × 2 mm × 0.5 mm. A low temperature of 105 K was achieved, although the expected low temperature was 96 K with a 10 mW heat load. Freezing of water vapor in the nitrogen gas at the cold end was a serious problem that was investigated as part of this work.

6. Conclusions

After cryocoolers were first coupled directly to specific applications starting in about the mid 1960s, the demand for improvements began. The early cryocoolers had rather short lifetimes and low efficiencies. Enough improvements were made over the next 20 years that they began to be developed for space applications by the mid-1980s. Many of the improvements in cryocoolers that came about as a result of trying to satisfy the requirements for space applications were soon spun off into some commercial applications. Advances in all five of the cryocoolers types in common use were made in the past 20 years. These advances have led to new applications that were not practical before. Still, many other applications could be possible with further improvements. Some of the recent trends taking place in cryocooler research were described here and included developments in thermoacoustically driven pulse tubes that have led such systems to reach temperatures below 20 K. Efforts now underway to operate regenerative cryocoolers at frequencies above 100 Hz should soon lead to significant reductions in size for the same cooling power. Large pulse tube cryocoolers tend to experience problems with nonuniform flow in both the regenerator and pulse tube that decreases the efficiency. Some successful methods for reducing the problem in the regenerator have been found, but further work is needed. The use of CFD modeling of the pulse tube and other components in the pulse tube cooler may soon lead to further understanding of how to reduce the nonuniform flow. The high cost of liquid helium in the last few years has led to the development of many commercial cryogen-free 4 K systems using pulse tube cryocoolers. Recent research on high frequency 4 K pulse tube cryocoolers and the associated regenerators operating with ^{3}He working fluid may provide a better understanding of the losses in these systems and provide guidance on how to significantly increase their efficiency. Finally, as many things in the electronic and detector world are moving into the microscale, the demand for matching microcryocoolers is increasing. Several efforts are underway now to meet those demands.

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