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Study of Refrigeration System for Achieving Cryogenic Temperatures

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Abstract: ***This study provides an overview of the common means of achieving cryogenic temperatures for useful exploitation, including both passive systems involving the use of liquid and frozen cryogens, as well as active cryo-refrigeration systems—commonly referred to as cryo-coolers. Separate subsections articulate the basic operating principles and engineering aspects of the leading cryo-cooler types: Stirling, pulse-tube, Gifford-McMahon, Joule-Thomson and Brayton. Because this field is very extensive, the goal of the study is to provide an introductory description of the available technologies and to summarize the key decision factors and engineering considerations in the acquisition and use of cryogenic cooling systems.***

Keywords: cryo-genic, frozen-cryogens, cryo-coolers, stirling, pulse-tube

1. Introduction

A sort of workingman's definition of cryogenic temperatures is temperatures below around 123 K, which equals -150°C or -238°F. In this temperature range and below, a number of physical phenomena begin to change rapidly from room temperature behaviors, and new phenomena achieve greatly increased importance. Thus, study at cryogenics temperatures typically involves a whole set of new temperature-specific discipline skills, operational constraints, and testing methodologies. One of these special attributes of cryogenics is the science and engineering of achieving cryogenic temperatures, both in the laboratory as well as in a sustained "production" environment. The latter can extend from a hospital Magnetic Resonance Imaging (MRI) machine, to a long-wave instrument on a space telescope, to a night-vision scope on a military battlefield. A number of technologies can provide the cooling required for these and other applications; the choice generally depends on the desired temperature level, the amount of heat to be removed, the required operating life, and a number of operational interface issues such as ease of resupply, sensitivity to noise and vibration, available power, etc.

2. Passive Cooling Systems

For many years, the use of stored cryogen systems has provided a reliable and relatively simple method of cooling over a wide range of temperatures—from below 4 K for liquid helium, to 77 K for liquid nitrogen, up to 150 K for solid ammonia. These systems rely on the boiling or sublimation of the low-temperature fluid or solid cryogens to provide cooling of the desired load. For solid cryogens, the temperature achieved may be modulated to a modest extent by varying the backpressure on the vented gas from atmospheric pressure down to a hard vacuum.

In most cases, stored-cryogen cooling technology is fairly well developed with proven design principals and many years of experience in the trade. The advantages of these systems are temperature stability, freedom from vibration and electromagnet interference, and negligible power requirements. The disadvantages are the systems' limited life or requirement for constant replenishment, the inability to smoothly control the cryogenic load over a broad range of temperatures, and the high weight and volume penalty normally associated with long-life, stand-alone systems.

In systems where the temperature stability and heat transfer associated with cooling with a liquid cryogen is advantageous, one can often extend the useful life of the cryogen or greatly minimize needs for replenishment by adding in a mechanical refrigerator with the cryogen dewar to either recondense the boiled off vapor and return it to the dewar, or to simply intercept a significant fraction of the parasitic thermal load entering the dewar.

The use of stored cryogens such as liquid nitrogen or liquid helium has often been the preferred method for cryogenic cooling of a wide variety of devices—from a laboratory apparatus to an MRI machine in a hospital setting. Cryogenic liquids can be used for cooling in a number of different states, including normal two-phase liquid-vapor (subcritical), low-pressure liquid-vapor (densified), and high-pressure, low-temperature single-phase (supercritical) states. Subcritical fluids such as low-pressure helium have long been the cooling means of choice for very-low-temperature (1.8 K) sensors for space astronomy missions.

Solid cryogens are mostly used below their triple point where sublimation occurs directly to the vapor state. They provide several advantages over liquid cryogens including elimination of phase-separation issues, providing higher density and heat capacity, and yielding more stable temperature control, which is desirable for many applications. Fig.1 describes the operating temperatures attainable with ten common cryogens that can be used to directly cool cryogenic loads or other components.

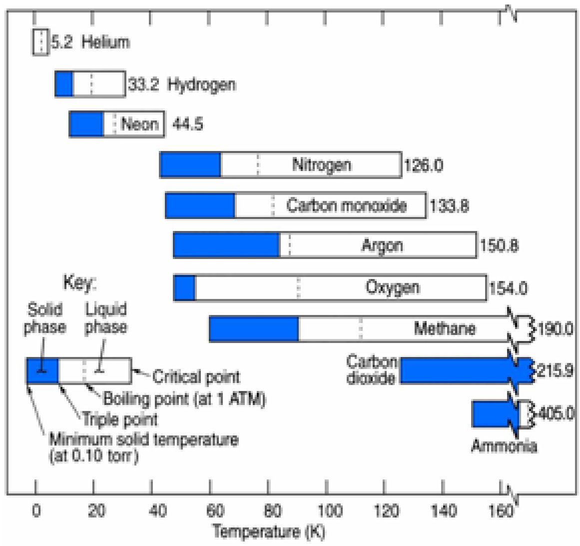

Figure 1: Operating temperature ranges for common expendable coolants

Each cryogen is represented by a bar that extends from its minimum operating temperature as a solid—based on sublimation at a vapor pressure of 0.10 torr—to its maximum operating temperature—its critical point, which is the maximum temperature at which a cryogen can exist as a two-phase liquid vapor. Within each bar, the region of solid phase is denoted by the shaded area defined at its maximum temperature by the cryogen's triple point, which is the maximum temperature at which a cryogen can exist as a solid. Above this, the cryogen's boiling point at a pressure of one atmosphere is noted by the dashed line. The use of 0.10 torr to define the lowest achievable temperature is for convenience, as the temperature can be lowered if the ability to pull a stronger vacuum is available.

3. Thermodynamic Principles of Cryogen Coolers

Fig.2 expands on the key fluid parameters noted in Fig. 1 via an idealized temperature-entropy (T-S) diagram for a pure cryogenic fluid. Since entropy is defined as the heat transferred divided by the temperature at which the change occurs, the T-S chart is not only useful to visualize the boundaries between fluid states, but to also quantify the amount of heat transferred when a fluid undergoes a change of state.

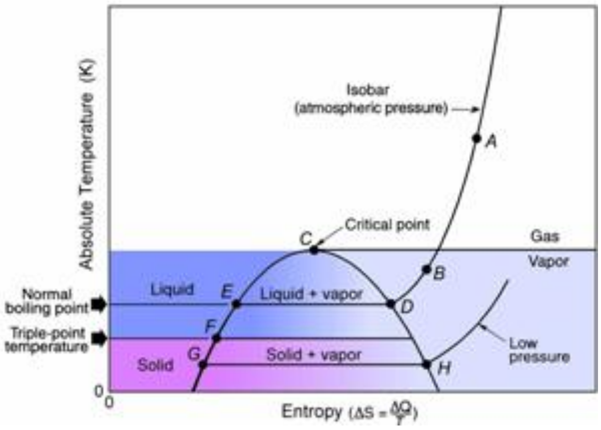

Figure 2: Idealized temperature-entropy diagram for a cryogenic fluid.

Starting with the point C, the apex of the dome is called the critical point, and the conditions at that point are called the critical pressure, critical temperature, etc. When the fluid is at or above the critical temperature, it can never exist in the liquid state, but will remain as a single-phase, homogeneous gas. Fluids stored under these conditions are sometimes called cryo-gases. The line described by curve ABD in Fig. 2 represents the path of a gas being cooled at constant atmospheric pressure. The horizontal line drawn at C represents the dividing line between a vapor and a gas. While they are technically in the same state, the points along the line DE represent a liquid and vapor mixture at constant temperature and pressure — point D being 100% saturated vapor while point E being 100% saturated liquid. As an example, for water, this DE line would be at 100°C, the boiling point of water at a pressure of one atmosphere. The change in energy from point E to D is the heat of vaporization. When a liquid is heated along this line, point E is also called the bubble point, because it is where the first vapor bubbles appear. Further cooling of the liquid from E to F reduces the vapor pressure, and eventually the liquid freezes into a solid. Point F is defined as the triple point (or melting point), where the fluid exists as solid, vapor, and liquid. For water, this would be the temperature of an ice/water mixture, i.e. 0°C. For a cryogen that is below the triple point temperature, such as point G, any addition of heat will cause the solid to sublimate, as opposed to melting to a liquid. For the conditions of point G, the heat of sublimation is given by the change in energy from G to H.

4. Cooling with Liquid Cryogens

Over the years, many liquid cryogenic systems have been developed, fabricated, and operated in both ground environments and in space. They cover a wide range of cryogen fluids and construction features in terms of stored volume, pressure and temperature limitations, and relative efficiency in terms of the parasitic heat leaks. Many of these systems utilize liquid helium for achieving temperatures between 1.4 K and 4 K or liquid nitrogen for achieving temperatures around 77 K. To achieve temperatures below 4.2 K requires that liquid helium be stored under partial vacuum conditions. At pressures from 10 to 40 torr, temperatures in the range of 1.4 K to 1.8 K are achievable with liquid helium.

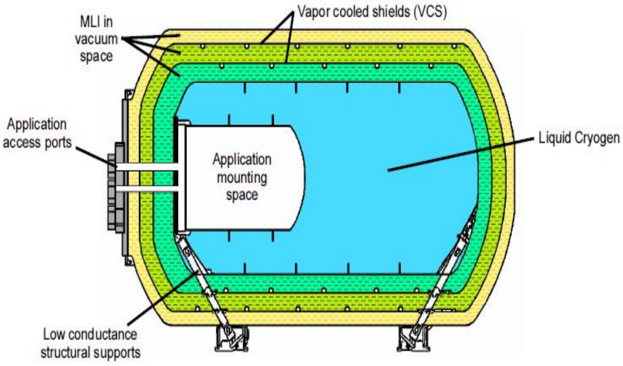

Figure 3: liquid cryogen dewar construction features

As illustrated in Fig. 3, liquid cryogen systems typically involve a nested storage tank concept whereby the inner tank, which holds the liquid cryogen, is suspended inside an outer vacuum shell with low-conductivity structural supports. These structural supports are typically made of low-conductivity tubes, struts or tension bands in order to achieve high structural efficiency and minimum conductivity between the two tanks. The gap between the two tanks is then evacuated and filled with Multilayer Insulation (MLI). In addition, a high efficiency dewar may also contain one or more strategically placed vapor-cooled shields (VCS) that are cooled by the evaporating cryogen as it vents from the inner tank.

5. Cooling with Solid Cryogens

A second efficient way to use stored cryogens is in the frozen state. As indicated in Fig. 5, the normal operating regime of a solid cryogen cooler is below its triple-point temperature. In this region, the addition of heat causes conversion of the solid directly into vapor through the process of sublimation, bypassing the liquid state. Operating below the triple point also eliminates the problems of fluid management and phase separation associated with fluid systems. From an efficiency point-of-view, working with the solid phase provides greater density (and thus lower storage volume) and higher heat content per unit mass of cryogen. Other advantages of a solid cooler are relative simplicity, absence of moving parts, absence of noise and vibration, excellent temperature stability, and no power requirements.

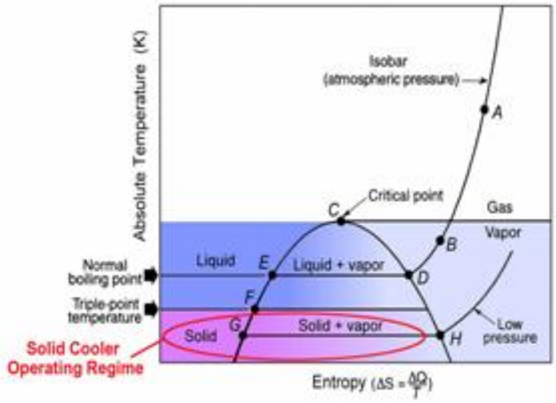

Figure 4: Solid cryogen operating regime

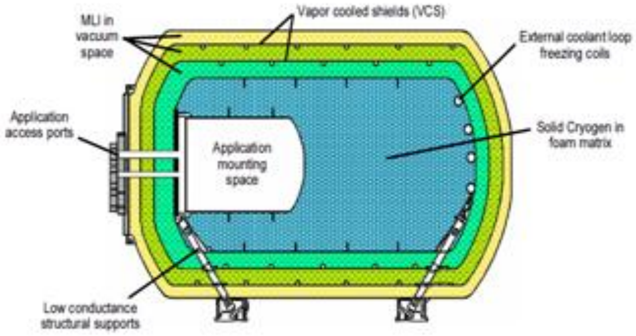

Figure 5: Solid cryogen dewar construction features.

As illustrated in Fig.5, solid cryogen dewar systems are fundamentally similar to liquid cryogen dewars in their structural support and thermal insulation systems. Both include a nested storage tank concept whereby the inner tank, which holds the solid cryogen, is suspended inside an outer vacuum shell with low-conductivity structural supports. As with liquid cryogen dewars, these structural supports are typically made using low-conductivity tubes, struts or tension bands in order to achieve high structural efficiency and minimum conductivity between the two tanks. The gap between the two tanks is evacuated and filled with Multilayer Insulation (MLI), and for high efficiency dewars, one or more vapor-cooled shields (VCS) may be strategically placed inside the gap.

6. Active Refrigeration Systems

For cryogenic applications where stored cryogens like liquid nitrogen and liquid helium are not readily available or are inconvenient to use, mechanical refrigerators, or cryo-coolers, are often the preferred design solution. The primary considerations that differentiate mechanical refrigerators from stored cryogen cooling systems are the issues of cryogen storage, resupply and safety for cryogen systems and the requirement for electrical power and a means of heat rejection for cryo-coolers. Because cryo-coolers, or cryorefrigerators, are typically driven by electrical powered compressors, means must be available to provide both the electrical power and the means to reject the resulting heat dissipation. The power dissipation issue is particularly important because the resulting heat reject temperature strongly effects the thermodynamic efficiency of the cryo-cooler. A second aspect of the electrically driven compressor is the strong likelihood of measurable levels of equipment vibration, EMI, and audible noise that may interact negatively with the intended cryogenic application. Achieving low levels of vibration and noise has been an important focus in the cryo-cooler development industry, and is an important distinguishing attribute of certain cryo-cooler types and constructions. Another key advantage of a cryo-cooler is the ability of a single unit to provide cooling over a broad range of temperatures, many with closed-loop temperature control.

7. Cryo-cooler

All mechanical refrigerators generate cooling by basically expanding a gas from a high pressure to a low pressure. The primary distinguishing feature between cycles is how the compression is accomplished, what pressure-ratio is used, what method of expansion is used to achieve the cold temperature, how well and where heat is rejected, and how well thermodynamic efficiency is maintained using heat exchangers, regenerators, and recuperators. Probably the most fundamental distinction between cryo-cooler types is the nature of the refrigerant flow within the cryo-cooler: either alternating flow (AC systems) or continuous flow (DC systems). This distinction is also denoted as regenerative systems versus recuperative systems based on the type of heat recovery heat exchanger that is applicable: regenerators for an alternating flow (AC system), or recuperators for a continuous flow (DC system).

8. Stirling Tube Cryo-coolers

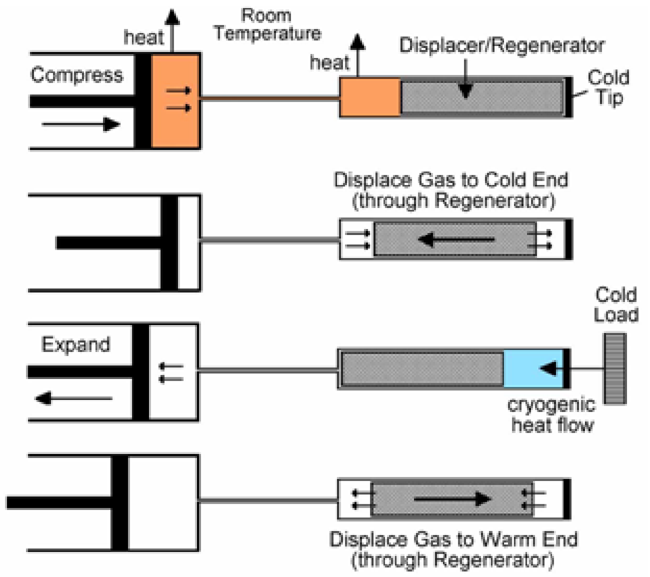

Figure 6: Schematic of Stirling cooler refrigeration cycle.

The cycle can be roughly divided into four steps, as follows:

- The cycle starts with the compressor compressing the gas in the expander cold finger. Because the gas is heated by compression, the displacer is used to position the expander's gas pocket at the warm end of the cold finger which is coupled to a heatsink to dissipate the generated heat.
- At the completion of the compression phase, the displacer moves to the left to reposition the expander's gas pocket to the cold end of the cold finger to ready it for the upcoming expansion phase. During this part of the cycle, the gas passes through the regenerator entering the regenerator at ambient temperature T High and leaving it with temperature TLow. Thus, the heat storage feature of the regenerator smooths out the cyclic temperature of the gas in the two ends of the expander cold finger.
- Next, the compressor enters its expansion phase, thus expanding and cooling the gas in the expander's coldfinger—adjacent to the cryo-cooler's cold load. This is where the useful cooling power is produced.
- In the final portion of the cycle, the displacer moves to the right to reposition the expander's gas pocket to the hot end of the coldfinger to ready it for the upcoming compression phase.

During this part of the cycle, the gas again passes through the regenerator entering the regenerator at the cold temperature TCold and leaving it with temperature THot. Thus, the heat storage feature of the regenerator again smooths out the cyclic temperature of the gas as it flows between the two ends of the expander cold finger.

9. Pulse Tube Stirling Cycle

The four cyclic phases of the pulse tube cooler are illustrated in Fig. 10. In this figure the displacer function of the pulse tube is noted by a virtual-displacer which represents the cold and hot boundaries of the stratified gas plug that oscillates back and forth in the pulse tube during the cooler's operation.

- As with the conventional Stirling cycle, the cycle starts with the compressor compressing the gas in the expander cold finger. Because the gas is heated by compression, the pulse tube's pneumatic circuit is used to position the expander's gas at the warm end of the regenerator which is coupled to a heatsink to dissipate the generated heat.

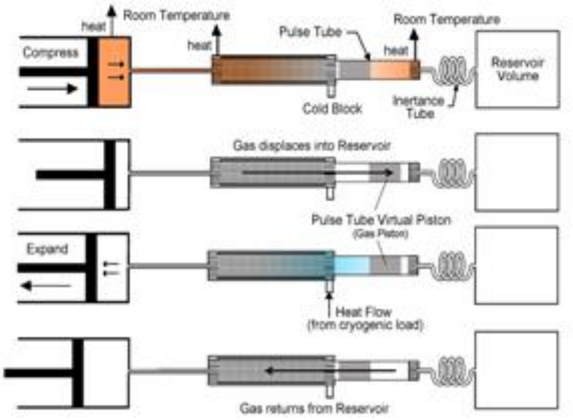

Figure 7: Schematic of pulse tube cooler refrigeration cycle.

- At the compression phase ends, the pulse tube's pneumatic circuit repositions the expander's gas to the cold end of the regenerator to ready it for the upcoming expansion phase. During this part of the cycle, the gas passes through the regenerator to dampen out the cyclic temperature variations and preserve the temperatures at the two ends of the regenerator.
- Next, the compressor enters its expansion phase, thus expanding and cooling the gas in the expander's coldfinger—adjacent to the cryo-cooler's cold load interface. This is where the useful cooling power is produced.
- In the final portion of the cycle, the pulse tube's pneumatic circuit repositions the expander's gas to the hot end of the regenerator to ready it for the upcoming compression phase. During this part of the cycle, the gas again passes through the regenerator to dampen out the cyclic temperature variations and preserve the temperatures at the two ends of the regenerator.

10. Gifford-McMahon cryo-coolers

The GM cooling cycle can be divided into four steps as follows:

- The cycle starts with the rotary valve connecting the expander to the high-pressure roomtemperature gas from the compressor. This fills the expander's gas pocket, which has been previously positioned at the warm end of the cold finger, with high pressure gas
- At the completion of the high-pressure filling phase, the displacer moves to the left to reposition the expander's gas pocket to the cold end of the cold finger to ready it for the upcoming expansion phase. During this part of the cycle, the gas passes through the regenerator entering the regenerator at ambient temperature TAmbient and leaving it with temperature TLow. Thus, the heat storage feature of the regenerator retains the temperature gradient between the warm and cold ends of the cold finger and smooths out the cyclic temperature variation of the gas.
- Next, the rotary valve connects the low pressure suction from the compressor return to the expander, thus expanding and cooling the gas in the expander's

coldfinger tip—adjacent to the cryo-cooler's cold load. This is where the useful cooling power is produced.

- In the final portion of the cycle, the displacer moves to the right to reposition the expander's gas pocket to the room temperature end of the coldfinger to ready it for the upcoming high high-pressure gas filling phase. Again, during this part of the cycle, the gas passes through the regenerator, and the heat storage feature of the regenerator smooths out the cyclic temperature of the gas as it flows between the two ends of the regenerator.

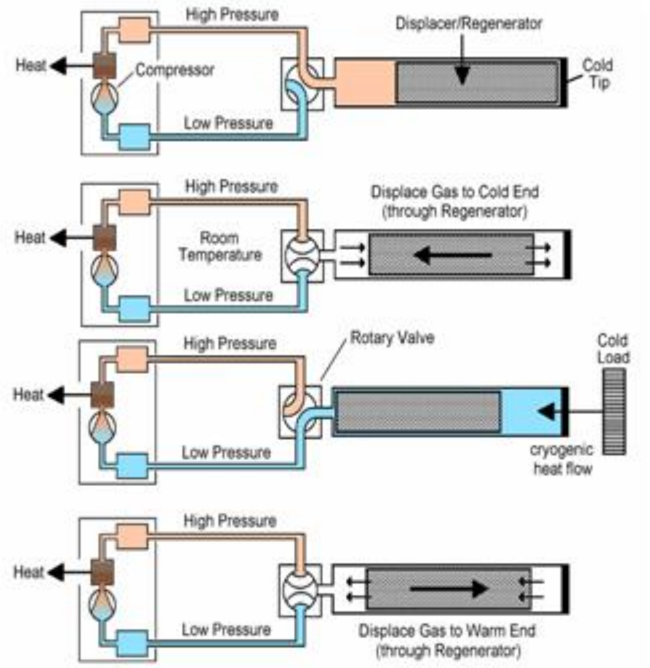

Figure 8: Schematic of Gifford McMahon refrigeration cycle.

11. Joule-Thomson Refrigeration Systems

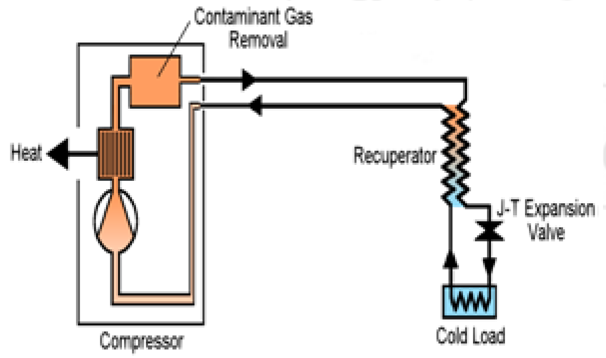

Figure 9: Basic mechanical setup of the closed JT cycle

Such systems incorporate a high pressure compressor to first pressurize the refrigerant stream to a relatively high pressure—much higher than that of a Stirling-cycle cooler, for example. Here, the heat of compression is extracted via heat exchange to an ambient-temperature heatsink. For the vapor compression or throttle-cycle version of the JT cycle, the refrigerant is chosen so that it is actually liquefied at this temperature and pressure; for the conventional JT cycle it is generally still a gas, but must be cooled below its inversion temperature before reaching the expansion valve. The refrigerant is next expanded through the JT valve, or throttle valve in the case of a liquid, to where it is used to cool the refrigeration load. Depending on the refrigerant gas and pressures used, the resulting cold refrigerant can be a pure gas or a mixture of gas and liquid. After cooling the load, the refrigerant is circulated back to the compressor for repressurization. For the case where the refrigerant is a liquid following the expansion process, the liquid may be contained in a reservoir or "evaporator" where it is boiled off as it is used to cool the load.

12. Conclusion

This study has provided an overview of the common means of achieving cryogenic temperatures, including both passive systems involving the use of liquid and frozen cryogens, as well as active cryo-coolers.

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