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DEPARTMENT OF AEROSPACE ENGINEERING

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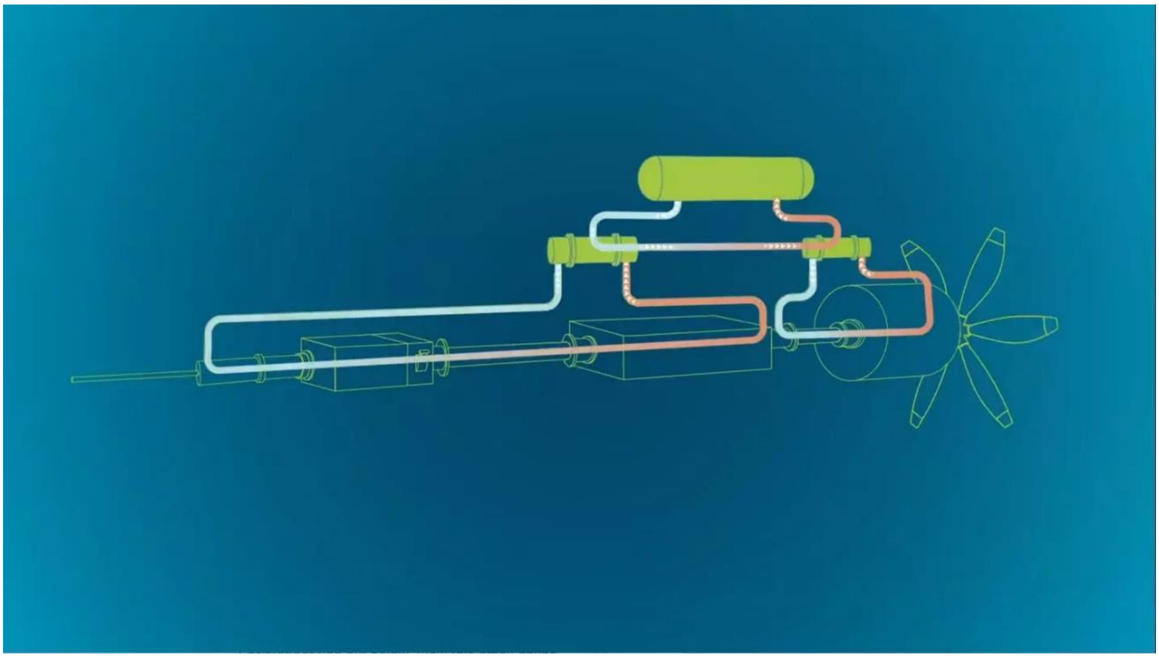
UNIT III - CRYOGENIC ENGINEERING

Superconductivity

Superconductivity is a phenomenon that occurs in materials that have zero electrical resistance and expel magnetic fields. Cryogenic systems are used to cool superconducting materials to reach the temperatures required for superconductivity to occur.



A major breakthrough in electric propulsion for long-range aircraft could soon be on the horizon. The presence of a cold source, in the form of liquid hydrogen, alongside superconducting technologies promises to unlock new possibilities. Today, the ASCEND demonstrator project by Airbus UpNext aims to mature these technologies to significantly boost the performance of electric- and hybrid-electric propulsion systems in future low-emission aircraft.

In 1911, Dutch physicist Heike Kamerlingh Onnes found himself preoccupied with one question: what happens to the electrical conductivity of pure metals at very low temperatures? During an experiment, he immersed a wire made of solid mercury into liquid helium, and to his astonishment, found the wire's electrical resistivity completely vanished at 4.2°Kelvin (-268.95°C).

He called the phenomenon "superconductivity," or the ability of certain materials to generate strong magnetic fields and conduct very high electric currents with practically zero resistance when exposed to very low temperatures. The discovery was so ground-breaking, it earned Kamerlingh Onnes the 1913 Nobel Prize in Physics.

Today, superconductivity has a variety of practical applications, including the following:

- Electrical power transmission cables
- Magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR) machines
- Particle accelerators and magnetic fusion devices
- Some electric motors and generators

However, superconductivity's applications in the aerospace industry have yet to be fully explored. Airbus UpNext is looking to change that with its latest ground-based demonstrator project ASCEND.

This ground-based demonstrator project led by Airbus UpNext aims to explore how cryogenic and superconducting technologies could boost the performance of electric and hybrid-electric propulsion in low-emission aircraft.

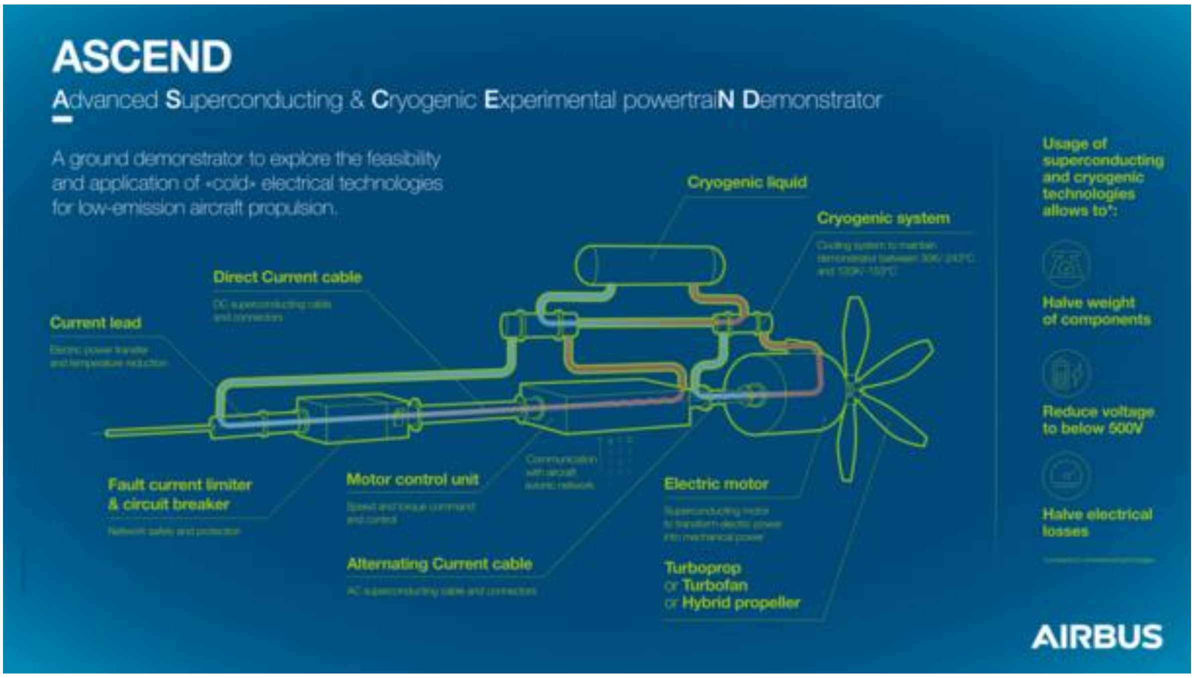
The twin power of cryogenics and superconductivity

One of the major challenges of scaling up electric propulsion to larger aircraft is the power-to-weight ratio. In other words, today's electrical systems simply do not meet the necessary power requirements without adding excess weight to the aircraft. But high-temperature superconducting technologies are emerging as a promising solution to this technical conundrum, notably by increasing power density in the propulsion chain while significantly lowering the mass of the distribution system.

This is where ASCEND comes in. The three-year demonstrator project aims to show that an electric- or hybrid-electric propulsion system complemented by cryogenic and superconducting technologies can be more than 2 to 3 times lighter than a conventional system—through a reduction in cable weight and a limit of 30kW/kg in power electronics—without compromising a 97% powertrain efficiency.

To achieve this objective, ASCEND features a 500kW powertrain consisting of the following components:

- A superconducting distribution system, including cables and protection item
- Cryogenically cooled motor control unit
- A superconducting motor
- A cryogenic system



“With the ASCEND demonstrator, we’ll adapt ground-based cryogenic and superconducting technologies to a fully electric powertrain to confirm their potential at aircraft level,” explains Ludovic Ybanez, Head of the ASCEND demonstrator. “Integrating these components will not only be a world first, but also an essential step towards future full-scale tests and flying demonstrators.”

Liquid hydrogen to cool conventional technologies

In addition to optimising the weight of the distribution system, another objective of ASCEND is to significantly increase the power density of the propulsion chain. This is a key consideration, as increasing the power of current electrical aircraft systems from a few hundred kW to the MW required for a fully electric aircraft is no easy feat. Simply put, more power increases weight and installation complexity, and generates more heat.

However, if a cold source at 20°K (-253.15°C), such as liquid hydrogen, is available on board, it can be used to cool the electrical systems. The superconducting components can then work to significantly improve the power density of the electric-propulsion systems.

Airbus is already looking into how liquid hydrogen could be used as fuel for an internal combustion engine or fuel cell as part of its ZEROe pre-programme. The ASCEND demonstrator will thus complement this research by providing additional insight into how cryogenic and superconducting technologies can support an ultra-efficient electric- and/or hybrid-electric propulsion system for future aircraft.

“With the ASCEND demonstrator, we’ll pave the way for a real breakthrough in electric propulsion for future aircraft,” says Sandra Bour Schaeffer, Airbus UpNext CEO. “The importance of this work can’t be understated: cryogenic and superconducting technologies could be key enablers to enhancing the performance of low-emission technologies, which will be essential to achieving our ambitious decarbonisation targets.”

Cryogenic cables

Cryogenic cables are specialized transmission lines engineered to maintain superconductivity at extremely low temperatures. Superconductivity is a phenomenon that occurs when certain materials exhibit zero electrical resistance when cooled below a critical temperature. This allows for the efficient flow of RF signals without any energy losses due to resistance.

These cables are typically constructed using high-performance superconducting materials, such as **niobium-titanium (NbTi)** or **niobium-tin (Nb3Sn)**, which have the ability to conduct RF signals without resistance when cooled to cryogenic temperatures. They are enclosed in a cryostat, a vacuum-sealed container that provides thermal insulation and maintains the low operating temperatures required for superconductivity.

Advantages of Cryogenic Cables

The use of cryogenic cables has a number of advantages, including:

- **Enhanced Efficiency:** Cryogenic cables enable the efficient transmission of RF signals with minimal energy losses, thanks to their superconducting properties. This translates into increased energy savings and improved overall system efficiency.

- **Increased Capacity:** Cryogenic cables have the potential to carry higher power and data loads due to their superconducting nature. This increased capacity can support the growing demands of modern technology and pave the way for future innovations.

Challenges When Using Cryogenic Cables

- **Cooling Infrastructure:** Operating cryogenic cables requires extensive cooling systems, which can be expensive and complex to implement. The cryostats needed to maintain the low temperatures can be large and bulky, making their installation challenging in certain applications.

- **Material Limitations:** Superconducting materials used in cryogenic cables are often brittle and sensitive to mechanical stress. This limits their flexibility and requires careful handling during installation and operation.

Applications of Cryogenic Cables

- **Energy Transmission:** Cryogenic cables have immense potential in the field of energy transmission. By minimizing energy losses during power transmission, they offer the promise of significantly more efficient electrical grids. These cables could revolutionize long-distance power transmission, enabling the transfer of renewable energy from remote locations to urban centers with minimal losses.

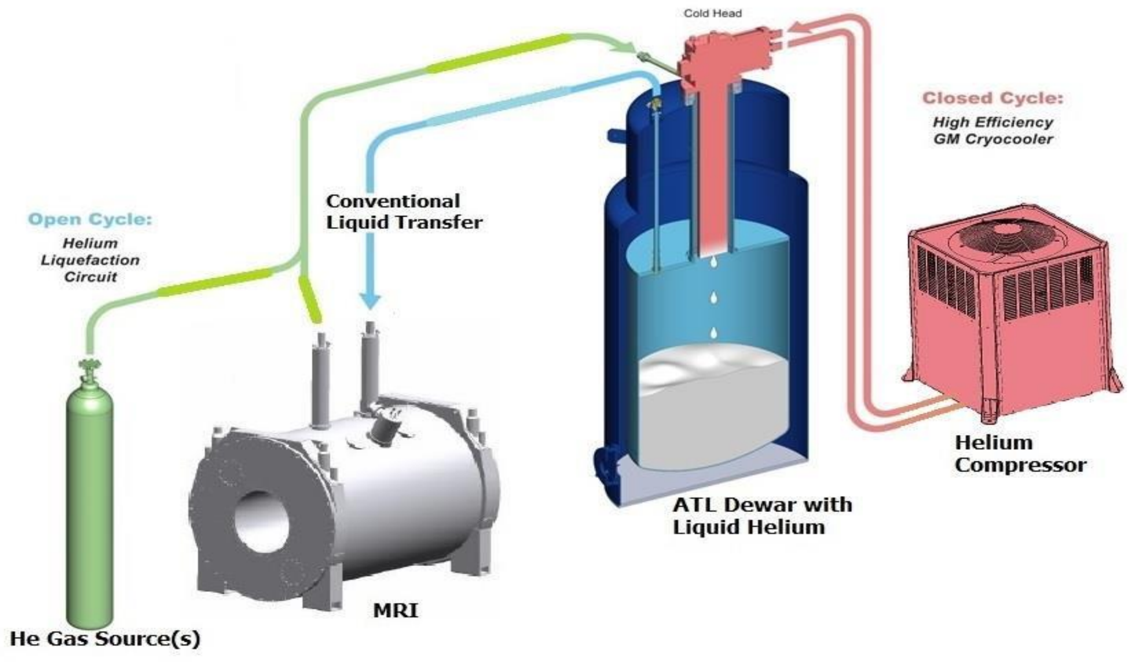
- **Particle Accelerators:** Cryogenic cables play a crucial role in particle accelerators, where high-energy particle beams are generated and guided through a complex series of superconducting magnets. These cables are employed to transmit power to the magnets while maintaining superconductivity, thereby reducing energy consumption and enhancing the overall efficiency of the accelerator systems.

- **Medical Imaging:** Magnetic resonance imaging (MRI) machines rely on powerful superconducting magnets to produce detailed images of the human body. Cryogenic cables are used to supply power to these magnets, ensuring a stable and homogeneous magnetic field for accurate imaging. The use of cryogenic cables in MRI systems enhances the imaging quality and reduces the energy requirements of these vital medical devices.

- **Research and Scientific Applications:** Cryogenic cables are extensively used in research laboratories and scientific experiments involving low-temperature environments. They enable the transmission of signals and power to various scientific instruments, such as spectrometers and detectors, ensuring accurate measurements and precise data acquisition.

Magnetic Resonant Imaging

MRI (magnetic resonant imaging) machines work by generating a very large magnetic field using a super conducting magnet and many coils of wires through which a current is passed. Maintaining a large magnetic field needs a lot of energy, and this is accomplished using superconductivity, which involves trying to reduce the resistance in the wires to almost zero. This is done by bathing the wires in a continuous supply of liquid helium at -269.1C. A typical MRI scanner uses 1,700 litres of liquid helium, which needs to be topped up periodically.



The problem is that helium is running out, as explained by chemist Peter Wothers in the Royal Institution's 2012 Christmas Lectures. Despite being the second most abundant material in the universe, helium is scarce on Earth as its lightness means it is not gravitationally bound to the atmosphere and is therefore constantly being lost to space. The majority of the world's helium supply is created through natural radioactive decay and cannot be artificially synthesised, meaning the gas is a non-renewable resource.

Cryogenic has developed a technique to cool magnets to close to absolute zero without needing liquid helium, only a small fixed amount of helium (equivalent of maybe half a liquid litre). The company is offering its magnets for use in a variety of imaging techniques including MRI, Nuclear Magnetic Resonance spectroscopy and Electron Spin Resonance spectroscopy.

The magnets can be cooled to low temperatures using mechanical refrigerators which run using electrical power and cooling water. The coolers rely on the compression and expansion of a fixed volume of helium gas supplied under pressure in a closed, self-contained circuit -- much like how an airconditioning unit would work. The helium gas remains cold and doesn't condense into a liquid.

Cryogenic's "dry" system eliminates the need for skilled manpower to transfer and handle the liquid helium. Director Jeremy Good explains to Wired.co.uk: "It's much like if you were trying to cool some drinks. Do you get a sack of ice cubes or a refrigerator?"

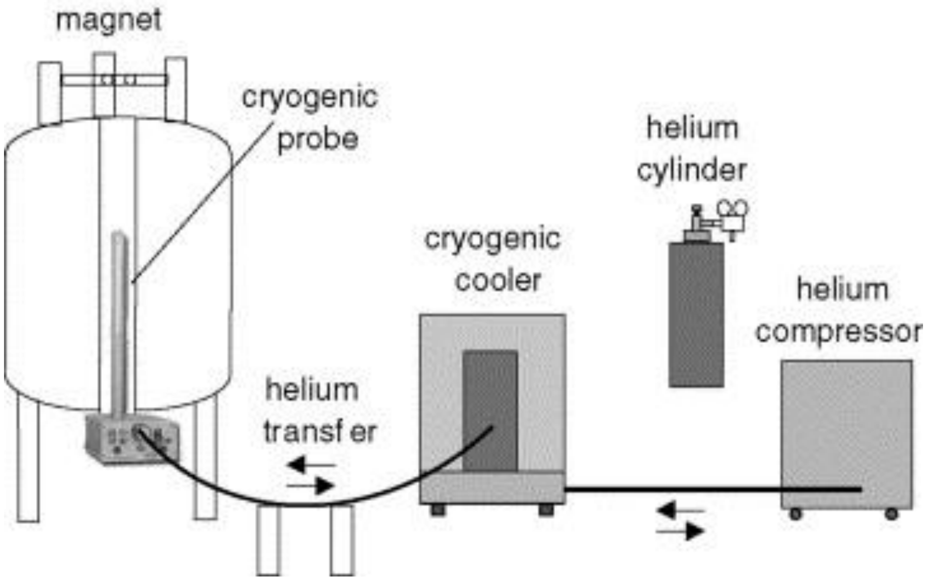
Cryogenic says that its system avoids a problem that sometimes occurs with MRI machines, called "quenching". This is when the wire in the electromagnet stops being superconducting and starts to generate a lot of heat. At this point, any liquid helium around the magnet rapidly boils off and escapes from the vessel housing the magnet. For this reason places using liquid helium need special ventilation facilities.

The managing director of Cyrogenic Jeremy Good, said in a statement: "In recent years major research laboratories have had to temporarily shut down multimillion-pound facilities because of these [helium] shortages and the problem will only get worse. Providing an alternative which doesn't rely on a regular supply of helium is essential to addressing this problem."

Cryogenic mainly focuses on MRI and other instruments based in research facilities, and doesn't currently make a cooling system for the full-body MRI machines that exist in hospitals. Good says that there are no fundamental reasons why Cryogenic's technology could not be used in this context and that he is in conversations with major manufacturers of those systems.

Nuclear Magnetic Resonance

Magnets for NMR experiments are required to have a high homogeneity, which can be maintained over a wide range of field. Experiments are performed at fixed frequency and the spectrum is obtained by sweeping the magnetic field. This requires the field to be stable in spatial homogeneity and change steadily and repeatedly over time.



As the spectra can vary considerably in width it is essential to be able to control the magnet current and therefore the field accurately over a wide range of field with sufficient precision to see narrow resonances.

In liquid helium filled systems it is common to operate the magnet in persistent mode and to perform magnetic field changes using a second sweep coil that can provide ± 0.1Tesla. This method is utilized to reduce liquid Helium consumption.

With a cryocooled magnet it is not necessary to reduce helium consumption, as there is no liquid to evaporate. Instead it is merely required to have accurate and smooth ramping of the magnet current.

With the power supplies provided by CRYOGENIC it is possible to set and measure the current accurately at the ppm level.

The system is delivered as an integrated system with magnet power supply and computer with software.

Cryogenic offers two types of Cryogen Free NMR systems:

- High field system with a magnetic field of 14.5 Tesla, 89mm room temperature bore and 5 ppm homogeneity over a cylinder 20mm long by 20mm diameter.

- Desk-top NMR with magnetic fields of 7 and 9.4 Tesla 52mm RT bore and <0.1 ppm homogeneity over 10mm DSV

The magnet is cooled by a single Sumitomo cooler operating at about 4K and is surrounded by a radiation shield at 40K. The cryocooler is specified to operate correctly in the stray field of the magnet and provide in excess of 10,000 hours continuous operation . The outer vessel is welded aluminum and the magnet operates in vacuum but a thermal buffer is fitted to absorb high short term heat loads for instance during rapid sweeps of the coil.

The magnet is made from NbTi and NbSn superconductors with truly superconducting joints to provide good persistent mode performance. A single magnet power supply is provided for the magnet. The ramp rates available are from approximately 10-8 to 10-3 per second of full value. A single current transducer is supplied to measure the current to 1ppm and output the result to the computer.

Sweep Coil

With the Cryogen-free system there is no requirement to have a persistent mode switch and to use a separate sweep coil to modulate about a given field. One can simply modulate the main power supply and not use a switch. However, as an option we offer a sweep coil with active compensation giving +/- 0.1Tesla and a second, separate power supply.

The mutual inductance of the sweep coil to the main coil will be designed to be a few (10) milli Henries.

Particle accelerators

These machines use electromagnetic fields to accelerate charged particles to high speeds and energies. They are used for a variety of applications, including research, particle therapy, and radioisotope production. High-energy particle accelerators use cryogenic equipment to create new matter, study its structure, and generate electromagnetic radiation.

Magnetic fusion devices

Cryogenic technology is used in fusion devices for a variety of purposes, including:

- Superconducting magnets: Cryogenic technology is used to cool superconducting magnets to ultra-low temperatures.
- Cryopumps: Cryopumps are used to create a high vacuum in the cryostat, which insulates the superconducting magnets.
- Current leads: Cryogenic systems cool the current leads that connect the room temperature power supply to the cryogenic temperature superconducting magnets.
- Thermal radiation shield: A thermal shield is placed between the ambient temperature and the 4 K temperature components to reduce thermal radiation heat loads.

Cryocoolers

A refrigerator designed to reach cryogenic temperatures is often called a cryocooler. The term is most often used for smaller systems, typically table-top size, with input powers less than about 20 kW. Some can have input powers as low as 2-3 W. Large systems, such as those used for cooling the superconducting magnets in particle accelerators are more often called cryogenic refrigerators. Their input powers can be as high as 1 MW. In most cases cryocoolers use a cryogenic fluid as the working substance and employ moving parts to cycle the fluid around a thermodynamic cycle. The fluid is typically compressed at room temperature, precooled in a heat exchanger, then expanded at some low temperature. The returning low-pressure fluid passes through the heat exchanger to precool the high-pressure fluid before entering the compressor intake. The cycle is then repeated.

There are six commonly used cryocooler types, which are divided into two categories — recuperative cycles and regenerative cycles. Schematics of the three most common recuperative cycles are shown in Figure 1. Schematics of the most common regenerative cycles are shown in Figure 2.

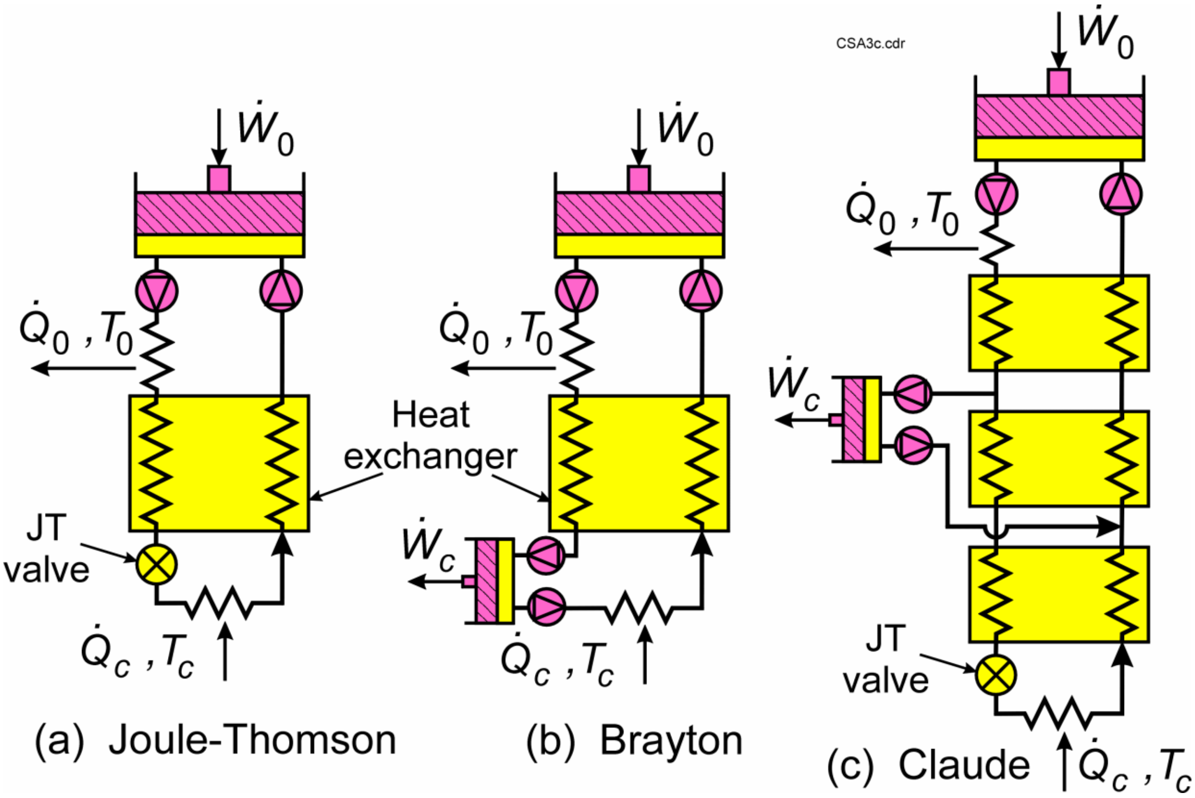


Figure 1. Schematics of the three most common recuperative cycles.

Recuperative Cycles

The recuperative cycles move the working fluid around a loop in one direction at fixed high and low pressures. The room-temperature compressor can either be a reciprocating-piston compressor with inlet and outlet valves or a unidirectional compressor without valves, such as a scroll or screw compressor. Efficient oil-removal equipment must be used in the high-pressure stream at room temperature to eliminate all traces of compressor oil from reaching the cold end and freezing. The heat exchanger for the recuperative cycles is known as a recuperator or recuperative heat exchanger. It has two separate flow channels—one for the high-pressure fluid and one for the low-pressure fluid. The low-temperature expansion can be with an orifice, capillary, or valve as in the Joule-Thomson (JT) cycle or with an expansion engine as in the Brayton cycle. The Claude cycle is a combination of the two in which an expansion engine is used for precooling and the JT expansion is used for the final expansion. Liquefaction often takes place in the final JT expansion.

he JT cycle normally uses a working fluid that is liquefied at the cold end, such as nitrogen for 77 K, hydrogen for 20 K, and helium for 4.2 K. For higher temperatures, mixed refrigerants of nitrogen and various hydrocarbons are often used to provide higher efficiencies.

Regenerative Cycles

The regenerative cycles, as shown in Figure 2, use oscillating flow and pressure with appropriate phase angles between the flow and pressure to achieve refrigeration at the cold end. Helium gas is almost always used as the working fluid. Maximum refrigeration occurs when flow and pressure are in phase near the cold end. The ideal phase angle is set by the phase of the displacer with respect to the piston in both the Stirling and Gifford-McMahon (GM) cycles. The displacer also recovers expansion work at the cold end and re-introduces it at the warm end to reduce the required input power from the compressor (pressure oscillator). Normally, there is no displacer in the pulse tube cryocooler, so the expansion work is lost unless a displacer is used at the warm end of the pulse tube. However, the lack of a displacer greatly reduces vibration at the cold tip. The flow impedance at the warm end of the pulse tube sets the phase between flow and pressure in the pulse tube cryocooler.

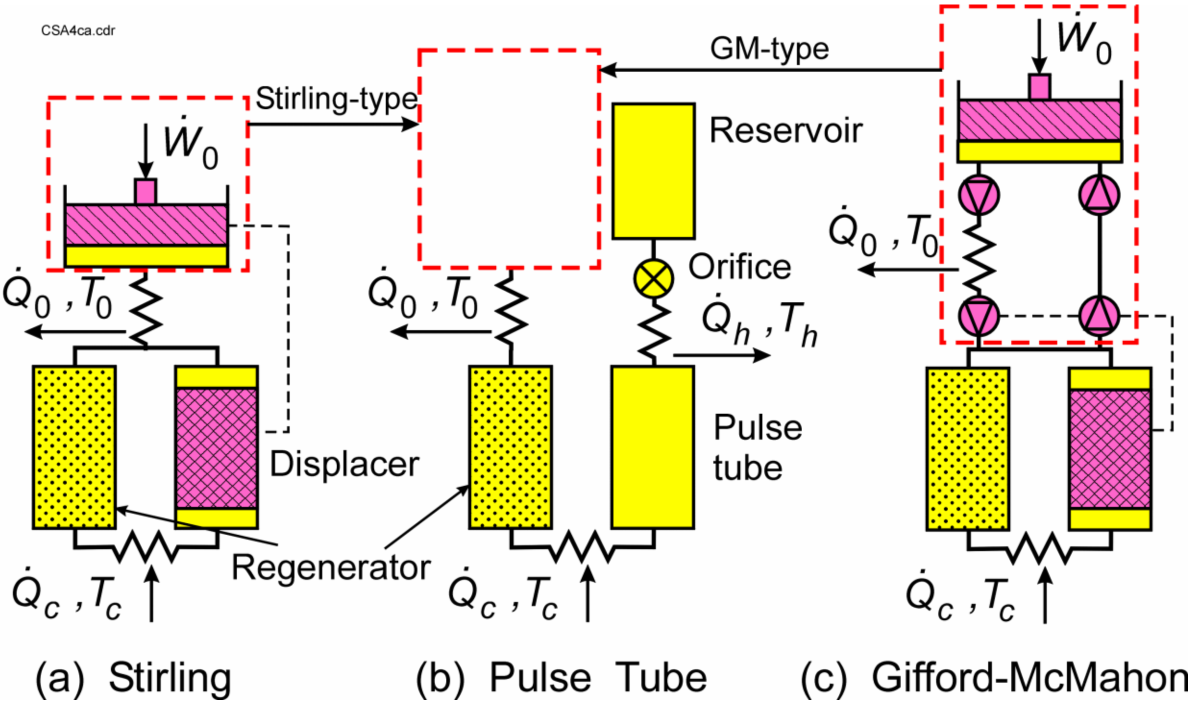


Figure 2. Schematics of the most common regenerative cycles.

The oscillating pressure in regenerative cryocoolers can be generated with a valveless compressor (pressure oscillator), as shown in Figure 2 for the Stirling cycle, or with valves that switch the cold head between a low- and high-pressure source, as shown for the Gifford-McMahon (GM) cryocooler. In the latter case, a conventional compressor with inlet and outlet valves (or a scroll compressor) is used to generate the high- and low-pressure sources. These compressors are commercial oil-lubricated air conditioning or refrigeration compressors modified for use with helium gas, and they are used primarily for commercial applications of cryocoolers where low cost is very important. Oil removal equipment can be placed in the high-pressure line where there is no pressure oscillation. The valves greatly reduce the efficiency of the system, but allow the use of mass-produced refrigeration compressors. Pulse tube cryocoolers can use either source of pressure oscillations, as shown in Figure 2, and they are referred to as either Stirling-type or GM-type depending on the type of compressor used. The Stirling compressors must be oil-free because oil removal equipment cannot be placed in the oscillating pressure region.

The Stirling cycle typically operates with frequencies in the range of 30-60 Hz, whereas the displacer and second set of valves in the Gifford-McMahon cycle operate at 1-2 Hz to achieve longer lifetimes with rubbing parts. Average pressures are often in the range of 1.5-3 MPa (15-30 bar) with oscillating pressure amplitudes of 10-15 % of the average pressure. Stirling-type pulse tube cryocoolers typically operate at 30-60 Hz, whereas the GM-type operate at 1-2 Hz. Average pressures and pressure amplitudes for pulse tube cryocoolers are about the same as those for the Stirling and GM cryocoolers.

The heat exchanger in regenerative cryocoolers is called a regenerative heat exchanger or regenerator. It has only one flow channel in which the flow changes direction every half cycle. The incoming warm stream is precooled during the first half cycle by heat transfer to the regenerator matrix, typically a packed bed of fine screen or packed spheres. The matrix has a high heat capacity to store the heat for a half cycle. During the second half cycle heat is transferred from the matrix to the returning cold stream.

Cold-end temperatures achieved with regenerative cryocoolers vary from about 3 K up to 300 K, though temperatures below 150 K are most common. The lowest temperatures of about 3 K are possible with GM cryocoolers and GM-type pulse tube cryocoolers. The Stirling and Stirling-type pulse tube cryocoolers are mostly used for temperatures above 20 K. They have the highest efficiencies of all cryocoolers, which can be in the range of 10-20 % of Carnot at 80 K.