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# New engineering research field – Cryogenic engineering

Masahide Murakami*
Institute of Engineering Mechanics and Energy, University of Tsukuba, Japan

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**Abstract -** Current research topics in the cryogenic engineering field are reviewed to indicate a new direction to the future technology development. This review starts from the definition of the cryogenic temperature range, and covers applications of superconductivity, cryogenically cooled detectors, liquid hydrogen, cryocoolers, and a number of current thermo-fluid dynamics research topics in cryogenic engineering. They are still actively treated in such international conferences as International Cryogenic Engineering Conference (ICEC), Cryogenic Engineering Conference (CEC), and International Cryogenic Material Conference (ICMC).

**Keywords:** Superconductivity, liquid helium, liquid hydrogen, pulse tube refrigerator.

## 1. Introduction

When the temperature is lowered, a number of interesting phenomena emerge (Radebaugh, 2007; Van Sciver, 1986), which have been mostly studied from the angle of physics. However, in the engineering field, some of them are now the source of much interest after it became understood that they could be extremely useful in our life. Some may be related to state-of-the-art technology, and will help to develop future industrial technologies. The temperature range of cryogenic engineering is generally considered to be below the liquid nitrogen temperature ($T_{LN2}$=78 K or -195 °C), but some phenomena may be included in the category of cryogenic engineering if the primary subject is considered to be intellectually related to cryogenic engineering (Haynes *et al*., 1983), even if the temperature is higher than $T_{LN2}$. Research about refrigerators (Walker, 1983) may be included in cryogenic engineering as well as in the field of refrigeration and air conditioning.

In the following, a number of engineering fields in contemporary cryogenics are introduced, some of which will be described in more detail in the subsequent sections. The most important is the application of superconductivity (Rose-Innes and Rhoderick, 1978; Bednorz and Müller, 1986; Leggett, 2006) of both metal superconductors that must be cooled by liquid helium to around 4 K and high critical temperature ($HT_C$) superconductors for which critical temperatures are around $T_{LN2}$ or lower. In fact, a major part of the current research efforts in cryogenic engineering is devoted to the application, and covers the development of new superconductive materials, practical applications of superconductors, and the cooling techniques of superconducting instruments and facilities. The development of cryogenic electronics or detectors should also be noted. Cryogenically cooled telescopes and detectors are the key to the success of space borne infrared ( Urbach and Mason, 1984; Murakami *et al*., 2010; Harwit, 2004) and X-ray (Takahashi *et al*., 2012) astrophysical observations. $HT_C$ superconductive filters (Simon *et al*., 2004) are becoming an essential element for the mobile phone sector in the USA. Liquid hydrogen (around 20 K) (Grant, 2003) could increase in importance in the energy field in the future; though liquid hydrogen is not the only choice for the storage and transportation of large amounts of hydrogen. Refrigeration engineering is, of course, an important research field to support all cryogenic engineering. Recently, pulse tube refrigerator (Radebaugh, 1990) has been the subject of a remarkable development, with the temperature range extending down to the temperature of liquid helium.

## 2. Current Status of cryogenic engineering

### 2.1 Cryogenic temperature range

A list of normal boiling points for typical substances is shown in Table 1. These temperatures are considerably lower than the temperature that can be reached by home refrigerators, around -20 °C (=253 K), or by dry ice, -79 °C (=194 K). These liquid cryogens have been generally used in cryogenic engineering (Haynes *et al*., 1983). However, recently even these extremely low temperatures have been generated using refrigerators, now called cryocoolers (Barr *et al*., 2004), because they are more convenient to operate than cooling by cryogen. Cooling by cryocoolers can be started just by switching-on, while in the case of cooling by cryogen, filling and refilling operations are indispensable and sometimes even troublesome.

*Author for correspondence: murakami@kz.tsukuba.ac.jp

**Table 1.** List of normal boiling points and melting points of typical substances.

| | Normal boiling point (K) | Melting point (K) at 1 atm |
|---|---|---|
| $^3$He | 3.19 | 3.2 (at 28.9 atm) |
| $^4$He | 4.22 | 4.2 (at 150 atm) |
| n-$H_2$ | 20.1 | 14.0 |
| Ne | 27.2 | 24.6 |
| $N_2$ | 77.4 | 63.2 |
| Ar | 87.3 | 83.2 |
| $O_2$ | 90.2 | 54.4 |
| Air | 83.0 | |

**2.2 Application of superconductivity**

Superconductivity will certainly be one of the key technologies for the coming advanced technological society. There are two kinds of superconductors: metal superconductors (Pb, Nb, $Nb_3Sn$, $V_3Ga$, and $Nb_3Al$) (Suenaga, 2007) and $HT_c$ superconductors (Freyhardt and Hellstrom, 2007). The critical temperature ($T_c$) of the former is mostly below 4 K (liquid helium temperature), and thus they need to be cooled by liquid helium or by special cryocoolers with a cooling capability down to liquid helium temperature. The latter have $T_c$ around $T_{LN2}$, and were discovered after 1986. However, even $HT_c$ superconductors are usually cooled down to the liquid helium temperature for sufficiently large temperature margins to $T_c$ in practical applications. The characteristic features of superconductors are exactly zero electrical resistance and a Meissner effect that is the complete ejection of magnetic field lines from the interior of the superconductor as it transitions into the superconducting state (Rose-Innes and Rhoderick, 1978). The occurrence of the Meissner effect indicates that superconductivity cannot be understood simply as the idealization of perfect electric conductivity in classical physics.

Superconducting Magnets: Superconducting magnets can generate far greater magnetic fields than normal electromagnets because no energy is dissipated as heat owing to zero electrical resistance (Wilson, 1986). They are used in MRI (Magnetic Resonance Imaging) systems (Bankman, 2000) (Fig. 1) in hospitals, in scientific equipment such as NMR (Nuclear Magnetic Resonance) (Slichter, 1978) spectrometers, mass spectrometers and particle accelerators, and in magnetic levitation trains (Chistopher, 2006) that are scheduled for 500 km/hr operation in Japan (Fig. 2). A superconducting high field magnet will also be an essential element in nuclear fusion power generation (Freidberg, 2007). Superconducting magnetic energy storage (SMES) (Wolsky, 2002) is as an energy storage technique for power generation. It is a system in which the special feature of the zero electric resistance of the superconducting cable is used, in which energy is stored by keeping the electric current flowing into a high magnetic field coil.

Superconducting DC Transmission: Superconducting DC transmission (Minervini *et al.*, 2009) is a promising superconductivity application, in which the superconducting cable is made of the superconductor copper oxide containing bismuth ($HT_c$ superconductor), and it may be cooled just to -196 °C (= 77 K) in liquid nitrogen. Liquid nitrogen is an inexpensive coolant compared to liquid helium, and the system will reduce transmission loss by two orders of magnitude compared to AC transmission.

Superconducting Electronics: Superconducting electronics will support the coming advanced information society as well as advanced medical and fundamental technologies. Some functions, which cannot be achieved or reached by semiconductors, are achieved by applying a superconductor. Most superconducting devices now use metal material of Nb, and an electric filter using oxide $HT_c$ superconductor has also been commercialized. SQUID (Superconducting Quantum Interference Device) (Gallop, 1990) is a device based on the principle of the macroscopic quantum effect of superconductivity, and it is not only used for scientific instruments, but for mineral exploration and non-destructive testing as well. In recent years, it has also served in heart and brain activity measurement devices in which the extremely weak magnetic field appearing on the body surface can be measured as a non-invasive inspection means to examine heart and brain disease. Heart MCG (Magneto CardioGraphy) and MEG (Magneto Encephalo Graphy) are spreading widely in the medical field.

Superconductive Devices: A STJ (Superconducting Tunnel Junction) detector (Tinkham, 1996 ) is a detector of radio waves, X rays (X-ray astronomy), and particle lines. It possess a remarkably high energy resolution compared with semiconductor devices, and a TES (Superconductive Transition Edge Sensor) (Irwin and Hilton, 2005) is also a sensitive radio wave and particle line detector. A Superconductor-Insulator-Superconductor (SIS) mixer (Blundell and Winkler, 1991), on the basis of the sharp nonlinearity of the Josephson junction, is a detector indispensable in radio astronomy, which catches the radio waves that come from the universe. The Josephson junction also has a unique application to voltage standard. The contribution of superconducting devices to quantum information technology is also promising. Research into Josephson devices and superconductive quantum bit using SQUID and the development of quantum computers are also continued energetically.

**2.3 Cryogenically cooled detector**

Descriptions of the applications of superconducting detectors are given in section 2.2. Cryogenic cooling of some high sensitivity detectors is also required from a different point of view. A typical example may be the infrared (IR) (Murakami *et al*., 2010) or X-ray [11] detectors for space borne astrophysical observation. The IR or X-ray astrophysical signals are extremely weak. The IR telescope must be cooled down to the 1 K range to reduce the thermal background noise (mostly IR radiation) from the telescope itself by using superfluid liquid helium (He II) (Murakami *et al*.,1989) or mechanical cryocoolers. For the detection of X-ray (and sometimes IR) astrophysical signals, high sensitivity bolometers are used, where the energy of an X-ray photon as a signal is converted into thermal energy that causes a small temperature rise to be detected. For the detection of the extremely weak energy of a photon, the detector and surroundings are cooled down to 50 mK with an adiabatic demagnetization refrigerator (ADR; Fig. 3) (Shirron, *et al*., 2002). The next generation X-ray astrophysical observation satellite, ATRO-H (Fig. 4) to be launched in 2016, will be equipped with this kind of X-ray detector array.

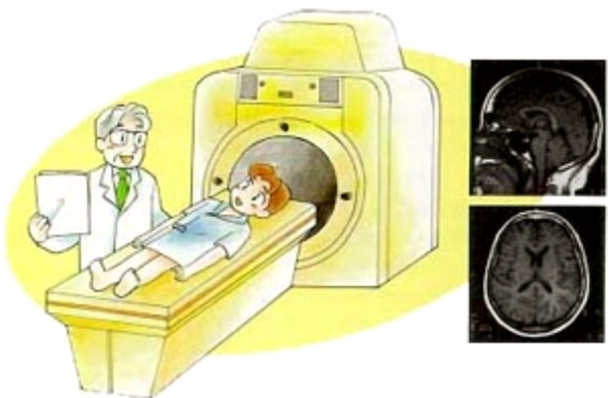


**Figure 1.** MRI (Magnetic Resonance Imaging) system and MRI images.

**Figure 2.** Magnetic levitation train that is scheduled for 500 km/hr operation in Japan.

**2.4 Liquid hydrogen**

Hydrogen is a reusable energy source (Grant, 2003) that may solve future energy problems. It is generally considered that gaseous hydrogen has rather low energy density. Therefore, it is usually liquefied to increase the density (790 times) for mass storage and transportation. The temperature of liquid hydrogen is 14-33 K (around – 250 °C), and thus liquid hydrogen is the second lowest temperature liquid after liquid helium. A heavy and bulky cryogenic container is needed for storage. However, recently, highly compressed hydrogen (up to 700 atm) (Zheng *et al*., 2012) has been developed for use, which is almost equivalent to liquid hydrogen in density, though the container is still heavy. Serious concerns relate to highly pressurized hydrogen becoming combustible gaseous hydrogen instantly if it leaks from a vessel. Liquefaction of hydrogen requires a large amount of energy, and liquid hydrogen is inferior to gaseous hydrogen, and thus a system for cold energy recovery should be included in the liquid-gas conversion process. For the application of liquid hydrogen, the para to ortho conversion (Ubaid *et al*., 2014), which is an exothermic process usually occurring after liquefaction, must be taken into account as an equivalent to heat generation. Here, liquid hydrogen will be discussed in the framework of cryogenic engineering, though liquid hydrogen is not the only medium for the storage and mass transportation of hydrogen.

Liquid oxygen-hydrogen combustion rockets (Black, 2012) are already at a practical stage, which are state-of-the-art high-performance rockets. On the other hand, liquid hydrogen does not seem promising for airplane fuel, because even liquid hydrogen requires too large fuel tanks owing to its low energy density. To solve this, the use of slush hydrogen (a mixture of liquid and particulate solid) (McNelis *et al*., 1995) that has a 16-20 % higher density than the liquid is considered. For power generation, hydrogen will be a fuel for use in fuel cells (FC) as well as for hydrogen combustion power plants. Hydrogen FC vehicles (Heetebrij, 2009) will be quite promising in the near future. On the other hand, the method of hydrogen fuel storage must be carefully chosen for vehicle application. Liquid hydrogen is not really suitable for private cars for general purposes, because the time for parking is longer than that for driving, and it would evaporate too much. Pressurized hydrogen or metal hydrate (hydrogen absorbing alloy) storage should be used instead. In that case, it is necessary to pay attention to the hydrogen embrittlement of the tank material and large weight of the tank.

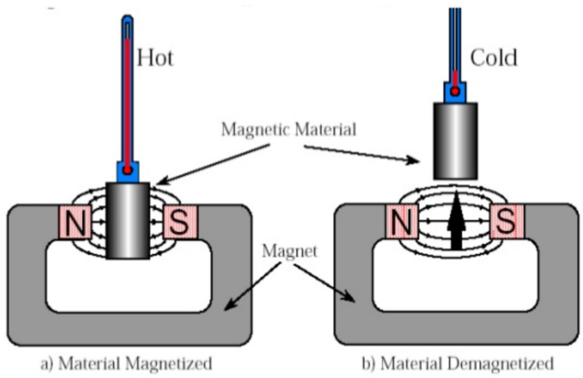



**Figure 3.** Working principle of an adiabatic demagnetization refrigerator.

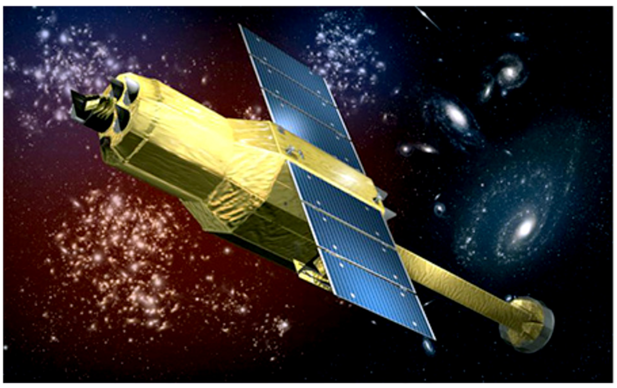
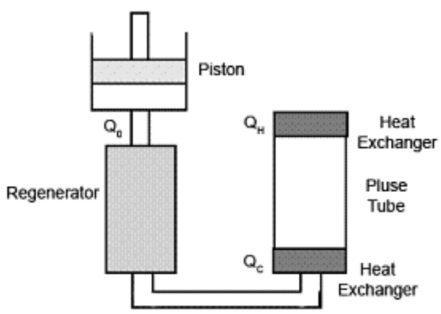


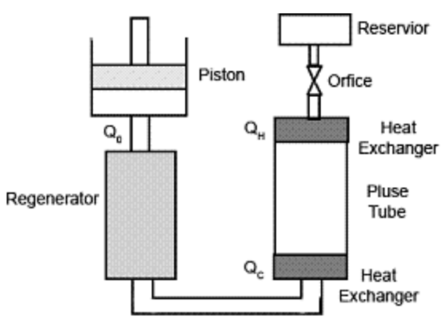
**Figure 4.** Next generation X-ray astrophysical observation satellite, ATRO-H, to be launched in 2016.

### 2.5 Cryocooler

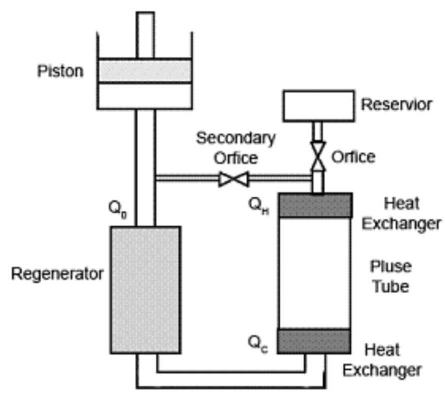
The temperature range that can be reached by mechanical refrigeration extends from the temperatures reached by household refrigerators and air conditioners down to liquid helium temperature (Barr *et al*., 2004). The liquid nitrogen temperature range is achieved by conventional cryogenic refrigerators such as Stirling or Gifford-McMahon (GM) refrigerators (de Waele, 2011). Even the liquid helium temperature can be reached by the above types of refrigerators provided the material for the regenerator is properly selected so that it has a large enough heat capacity in the temperature range. A recent trend in cooling for this temperature range has been the use of cryocoolers instead of liquid helium. The tedious filling of liquid helium cooling has been replaced by simply switching-on the MRIs. In space cryogenics, this general tendency of not using liquid helium as the coolant continues. Some space borne infrared telescopes are launched under room temperature conditions, and cryogenic cooling is started first by radiation cooling and then by switching-on cryocoolers after reaching the satellite's orbit (Nakagawa *et al*., 2014). According to this cooling scheme, it becomes unnecessary to load liquid helium, which means the elimination of a heavy and bulky vacuum shell of the cryostat and a liquid helium tank, and thus a telescope with a larger mirror can be launched and a longer cold life can be realized. Reflecting this technical trend, developments in cryocoolers have been actively achieved. The development of pulse tube cryocoolers (Radebaugh, 1990), is noteworthy, which were invented in the 1960's (Fig. 5). This type of cryocooler is characterized by the elimination of any moving parts in the cryogenic temperature area, and thus by its simplicity in structure, low mechanical vibration, long life, and high reliability. The original configuration (basic pulse tube) was a simple tube structure with a regenerator at one end, and the cooling performance and the efficiency were rather low. Then, an orifice type with a reservoir at the other end was invented. Now, a double inlet type pulse tube that can generate a liquid helium temperature is in practical use.




Basic pulse tube refrigerator




Orifice pulse tube refrigerator.




Double inlet pulse tube refrigerator.

**Figure 5.** Three types of pulse tube refrigerator: basic, orifice, and double inlet pulse tube.

**2.6 Current research topics in cryogenic engineering**

Thermophysical Properties: Software development of thermophysical properties of cryogens is important for cryogenic engineering (AIST). Many software packages are now commercially available, which are now established as a business. Software development extends to some kinds of mixtures of low temperature substances.

Thermal Insulation: Thermal insulation is indispensable for storage and transportation of the cryogen as well as for the cryostat, otherwise the cryogen will be lost in a short time and large amounts of boil-off gas (BOG) can be dangerous (explosive) with hydrogen. The most reliable method is vacuum insulation using multi-layer-insulation (MLI) (Donabedian and Gilmore, 2002; Savage, 2003), which is composed of a pile of multi-layered (10 to 50 layers) thin films with vacuum deposition of low emissivity metal (usually Al) on one or both sides. MLI has been conventionally used as excellent thermal insulation for satellites. Research is still continuing for even higher insulation performance and advanced implementation of MLI. However, in some cases, MLI may not be suitable for the construction of a very large storage tank. In such cases, perlite vacuum insulation (LaHousse, 1992) or some other new insulation is used instead. In general, the thermal performance of insulation for liquid hydrogen and helium storage must be better by a factor of 10 than that for liquid nitrogen at the same rate of BOG.

Thermo- and Fluid-dynamic Behavior of Cryogenic Fluids: There are several specific characteristic features of cryogenic fluids when compared with common room temperature fluids (Van Sciver, 1986; LaHousse, 1992). Most thermophysical properties of cryogenic fluids are more sensitive to temperature variation than fluids at room temperature. The temperature rise caused by heat input is larger than that for fluids at room temperature at a fixed heat input because the specific heat of the substance becomes smaller as the temperature decreases. However, the thermo- and fluid-dynamic behavior of cryogenic fluids is not essentially different from those of room temperature fluids, except for superfluid helium (Van Sciver, 1986). Of course, all experiments with cryogenic fluids must be conducted within a confined narrow space in a cryostat for the sake of thermal insulation and isolation.

Cryogenic Materials: Measurements of the physical properties of cryogenic materials are important as well as those of cryogenic fluids, which also must be conducted in a cryostat (Ishikawa *et al*., 1993). Now, applications of structural materials in a low-temperature environment are increasing, such as in liquid hydrogen-oxygen rockets, maglev trains, and fusion power plants. There is a special significance for the measurement of the material strength of cryogenic structural materials, because there is a possibility that cold brittleness will occur, which is in contrast to ductile fractures in common materials. Composite materials are also used in cryogenic applications.

**3. Summary**

Current research into cryogenic engineering fields that are of interest and may lead to sound developments in future technology was reviewed. Specific cryogenic equipment is needed to initiate cryogenic engineering study, and thus preparation is not easy in terms of funding and time. It, however, would be a good place to start from liquid-nitrogen related studies and then expand to superconductivity related studies in the next stage. The author hopes that this article will be useful for future development of research.

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