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A review of Magnetic Refrigeration Technology

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Abstract-- **This paper reviews the magnetic refrigeration technology that is a novel cooling method utilizing magnetic field to obtain low temperature. The key component of the refrigeration is a novel magnetic refrigerant which should possess sufficiently large magneto-caloric effect so that a pseudo-Carnot magnetic refrigeration cycle can cover reasonably large temperature span. Otherwise, a regenerative concept should be employed to expand the temperature span of the refrigeration cycle. There is a growing interest in magnetic refrigeration as a viable refrigeration technology not only for cryogenics as well as room temperature range. This paper covers historical developments, fundamental concepts, key components, application classification, and recent research trend of magnetic refrigerators.**

1. INTRODUCTION

Magnetic refrigeration is a cooling method utilizing magneto-caloric effect of a material. It has been used for several decades as a useful technique to obtain temperatures below 1 K. However, in the last ten years, the technology has also been evolved for refrigeration applications at temperatures above 1 K, even at room temperature. Magnetic refrigeration was originally developed for reaching sub-Kelvin temperature where gas expansion could not be utilized to produce cooling effect. In the case of gas refrigeration technology, the temperature of gas is increased when it is compressed due to receiving external work. After the compressed gas reaches thermal equilibrium with its environment, it can be expanded by a some control device (In other words, this ideal process is often called a reversible adiabatic expansion process.) to obtain low temperature. Like this well-known gas expansion technique, some solid can be magnetically compressed and expanded to result in temperature change. A paramagnetic material near Curie temperature where it makes a transition from ferromagnetism to paramagnetism, can possess large enough magneto-caloric effect to be useful for cooling other objects. While one mode of the magnetic refrigerator is a one-shot process type for approaching zero Kelvin, the other mode of a continuously operating magnetic refrigerator with reasonable refrigeration capacity has been in demand for engineering applications. The present article summarizes many aspects of magnetic refrigeration; historical developments, fundamental concepts, key components, application classification, and recent research trends.

2. HISTORICAL DEVELOPMENTS OF MAGNETIC OF REFRIGERATION

Magnetic cooling method had been known for many years, but the first important historical experimental demonstration was done by W.F. Giauque, who in 1933 achieved temperatures below 1 K [1]. Since 1933, many devices utilizing magneto-caloric effect have been developed to reach temperatures as low as 10^{-8} K. While most early attempts to approach absolute zero Kelvin relied on 'one-shot' devices, there have been efforts notably since 1950, to develop continuously operating magnetic refrigerators. Scientists as well as engineers have paid attention to developing a closed-loop magnetic refrigeration cycle to provide continuous cooling effect for various engineering purposes. Such magnetic refrigerators must have *a mechanism to transport heat from the magnetic refrigerant to the warm- and cold-end heat reservoirs*. Heer et al. [2] in 1954 and Zimmerman et al. [3] in 1962 used lead superconducting thermal valves as heat switches to control heat flow. Mechanical contact switches were explored by Collins et al. [4] in 1953 and Numazawa [5] in 1993. The heat pipe or thermosyphon has also been explored as a thermal switch by Nakagome (1984) [6] and Hakuraku (1985) [7].

Pratt et al. [8] and Steyert [9] developed magnetic refrigerators by rotating magnetic refrigerants around strong magnetic field in 1977 and 1978. Barclay et al. [10] and Delpuech et al. [11] devised reciprocating machines to magnetize and demagnetize the magnetic refrigerant respectively in 1979 and 1981. On the other hand, as a static device, Hakuraku [7] et al. in 1985 and Numazawa [5] et al. in 1993 utilized superconducting magnets to provide statically changing magnetic field. There was no relative movement between a magnetic refrigerant and a magnet. The superconducting magnet with changing current magnetized and also demagnetized the magnetic refrigerant. Either static or dynamic, these machines were all based on simple magnetic Carnot cycle concepts. The temperature span of the magnetic refrigerators, therefore, was rather narrow. Regenerative magnetic cycles, which we would explain later in more details, were proposed by Van Geuns [12] in 1966. This concept is similar to what has been already applied to other gas refrigeration systems such as Stirling, G-M, and pulse tube refrigerators. A regenerator serves as a temperature isolation device that separates the high temperature part and the low temperature part of the refrigerator by just allowing periodic heat exchange between the working fluid and the solid regenerator. In the case of regenerative magnetic refrigeration, the magnetic refrigerant is considered an active regenerator compared to the passive one which is usually adapted in gas refrigeration system. The inherent advantage of regenerative magnetic cycle is to be able to extend the temperature span of the cycle beyond the limited capability of the simple magnetic Carnot cycle. Taussig et al. [13] theoretically and also experimentally researched a regenerative magnetic refrigerator for 4.2 K utilizing thin magnetic refrigerant plates. In 1994, Jeong et al. [14] developed a tandem regenerative magnetic refrigerator for 1.8 K with two packed-bed magnetic columns. Those magnetic refrigerators were all static in that their superconducting magnets handled varying electrically stored energy. The latter system was uniquely consisted of two identical superconducting magnets to reduce the electrical energy flow between the magnetic refrigerator and its surrounding power supply.

More recently, there have been growing research efforts for room temperature refrigeration and hydrogen liquefaction system. Researchers at Astronautics Corporation in USA have been developing magnetic refrigeration devices with the aim of penetrating the air-conditioning market [15]. They demonstrated the ability to produce a no-load temperature span of approximately 25 K using 3 kg of Gd and a 5 T applied field [16]. An applied load of just over 600 W could be sustained with a temperature span near 10 K. Perhaps a more important result of this work was the demonstrated ability to provide cooling with an applied field of only 1.5 T which is within the range of rare-earth permanent magnets. Subsequently, a permanent magnet device was developed with a wheel of refrigerant rotating through the high field region [17]. The heat transfer fluid was water and a series of different refrigerants were tested. Maximum no-load temperature spans of approximately 24 K were obtained with a range of operating conditions and frequencies as high as 4 Hz were reported. In addition, results using a layered regenerator consisting of equal masses of Gd and $Gd_{0.94}Er_{0.06}$ were compared to Gd and a first-order material $La(Fe_{0.88}Si_{0.12})_{13}H$. Other research groups have constructed permanent magnet devices using reciprocating and rotary designs [18-21].

Researchers at the University of Victoria in Canada have concentrated on regenerator analysis and design using a reciprocating test apparatus. The experimental apparatus uses a superconducting magnet which allows testing to be carried out with applied fields as high as 5 T [22]. To date, AMRs (Active Magnetic Regenerators) consisting of one, two and three different materials have been tested under a variety of operating conditions [22-24]. They have found that layering of second-order materials can increase achievable temperature spans and cooling powers as compared to single materials, but higher performance comes with a reduced range of operating points. Using a 2 T applied field, a no-load temperature span of just over 50 K was achieved using an AMR consisting of equal volumes of Gd, $Gd_{0.74}Tb_{0.26}$, and $Gd_{0.85}Er_{0.15}$. At 1.5 T, the same AMR produced a maximum temperature span of ~43 K. It appears that higher performance is possible if the frequency and fluid flux can be further increased. The apparatus has a maximum operating frequency of 1 Hz and fluid flow is limited by the operating pressure of the gas circuit (~10 atm.) Other experiments using three-materials in a layered configuration and an applied field of 5 T produced a no-load temperature span of ~85 K. A parallel modeling program is being used to help optimize the composition of multi-material regenerators and the operating parameters. Magnetic interactions in an AMR are also being studied [25].

In Japan as a WE-NET (World Energy Network) program, a hydrogen liquefaction system by magnetic refrigeration is seriously pursued [26]. Ohira et al. first used $Gd_3Ga_5O_{12}$ (GGG) as a magnetic refrigerant for a magnetic refrigerator to liquefy hydrogen [27]. More recently, a better magnetic refrigerant (poly crystal 20 % Gadolinium doped dysprosium Aluminum Garnet, DGAG) was developed for hydrogen liquefaction system [28]. The hydrogen liquefaction system is being developed as the combination of the precooling part and the liquefaction part. The temperature span of the liquefaction system was very small, but achieved high Carnot efficiency. The next challenge is to extend the heat rejection temperature of the magnetic hydrogen liquefier to 77 K and this is considered as a great milestone in magnetic refrigeration research. This task is now seriously being investigated by a regenerative method.

3. PRINCIPLE OF MAGNETIC REFRIGERATION

3.1. Magneto-thermodynamics

Magnetic refrigeration utilizes the magneto-caloric effect of a certain material. To describe how useful the magneto-caloric effect is for producing low-temperature, a general thermodynamic energy relation is first considered, including the term representing magnetic work.

$$dU = TdS - PdV + \Sigma\mu_i dN_i + \mu_0 VHdM \qquad (1)$$

where U is the internal energy, S is the entropy, P is the pressure, V is the volume, H is the magnetic field, M is the magnetization per unit volume, μ_i is the chemical potential of i species, and μ_o is the magnetic permeability of free space ($= 4\pi \times 10^{-7}$ H/m). With constant volume and in the absence of chemical reaction, (1) reduces to:

$$dU = TdS + \mu_0 VHdM \qquad (2)$$

Now, the entropy change of magnetic material can be expressed by two independent variables; T and H.

$$dS = \left(\frac{\partial S}{\partial T}\right)_H dT + \left(\frac{\partial S}{\partial H}\right)_T dH$$
$$= \frac{C_H}{T} dT + \mu_\circ V \left(\frac{\partial M}{\partial T}\right)_H dH \qquad (3)$$

where the Maxwell relation $\left(\frac{\partial S}{\partial H}\right)_T = \mu_\circ V \left(\frac{\partial M}{\partial T}\right)_H$ is used.

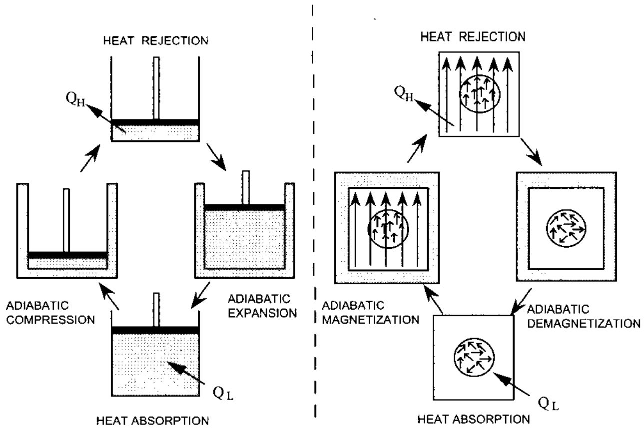
From (3), the *reversible adiabatic temperature change upon a magnetic field change* is derived as follows.

$$dT = -\frac{T}{C_H} \cdot \mu_\circ V \left(\frac{\partial M}{\partial T}\right)_H dH \qquad (4)$$

Generally, in the temperature range of the magnetic refrigerator, magnetization decreases at the same magnetic field as temperature increases. The temperature of magnetic refrigerant, therefore, decreases when it is demagnetized. The principle of magnetic refrigeration is based on this fundamental magnetic and thermal coupling which is called the magneto-caloric effect.

3.2. Comparison between gas compression and magnetic refrigeration cycles

The easiest way to understand magnetic refrigeration is to compare it with common gas refrigeration. The magnetic refrigeration cycle is typically composed of four processes as shown in Fig. 1, which illustrates two ideal cycles, one based on gas in the left and the other based on magnetic material in the right hand sides. Clearly the two cycles are in essence identical thermodynamically. Just as the working fluid in a gas compression cycle undergoes a mechanical compression and expansion, so does the solid magnetic refrigerant magnetically. The four fundamental processes are simply described as follows.



Gas cycle Magnetic cycle

Fig. 1. Comparison between vapor compression-expansion refrigeration and magnetic refrigeration cycle.

TABLE I
ANALOGY BETWEEN THE GAS COMPRESSION REFRIGERATION CYCLE AND THE MAGNETIC REFRIGERATION CYCLE

Gas Refrigeration Cycle	Magnetic Refrigeration Cycle
Pressure (P)	Magnetic field (H)
Volume (V)	Magnetic moment ($-\mu_0 VM$)
Mechanical compressor	Magnetic compressor
Mechanical restriction of molecular motion	Magnetic restriction of magnetic moment

(1) Adiabatic magnetization process

Magnetic moment inside the magnetic refrigerant is aligned to the direction of external magnetic field as it increases.

(2) Heat rejection process

Due to the magneto-caloric effect during the previous magnetization process, magnetic refrigerant is warmed up. The generated heat, thus, needs to be transferred to its surroundings during this heat rejection process.

(3) Adiabatic demagnetization process

As the magnetic field decreases, magnetic moment of the material returns to its original random state resulting in low temperature.

(4) Heat absorption process

Cold magnetic refrigerant during the adiabatic demagnetization process is now ready to absorb heat from its surroundings.

Table I summarizes the analogy between gas compression and magnetic refrigeration cycles by showing relevant corresponding parameters.

4. KEY COMPONENTS OF MAGNETIC REFRIGERATOR

A successful magnetic refrigerator requires not only a magnetic refrigerant with sufficient magneto-caloric effect but also an efficient heat transfer mechanism between the magnetic refrigerant and its surroundings. Fig. 2 shows the schematic diagram of a magnetic refrigerator. Sometimes, the auxiliary components in the system may generate too much entropy which nullifies the small refrigeration effect produced by the magnetic refrigerant. It is, therefore, extremely important to design all components very carefully to be able to maximize the possible available magneto-caloric effect.

(1) Magnetic refrigerant

This is a key component of the magnetic refrigerator which fundamentally enables to pump heat. Paramagnetic materials or ferromagnet/ferrimagnet materials near Curie temperature are useful with their relatively large magneto-caloric effect. As shown in Table 2, there are numerous magnetic materials for the candidates of magnetic refrigeration. Not so many materials, however, have been practically utilized for magnetic refrigeration. It is theoretically possible to cover the whole temperature range from cryogenic to room temperature by magnetic refrigeration, but we still need more breakthrough in material science to construct such a practical system because most materials have relatively small magneto-caloric effect compared to their lattice specific heat, especially at non-cryogenic temperature range.

(2) Magnet

Strong magnetic field is indispensable to produce large magneto-caloric effect with a given magnetic refrigerant. The magnetic field is usually generated by superconducting magnet either in steady or varying modes. Using a steady-field superconducting magnet is simple in terms of electric power control, but it requires cyclic displacement between the magnetic refrigerant and the magnet to produce magnetization and demagnetization effects. Since this relative movement requires very large magnetic interaction force, a double-acting or force-canceling mechanical device is often incorporated to reduce the actuation force. In the case of a varying-field superconducting magnet, the mechanical arrangement of the magnetic refrigerator is very simple. On the other hand, the electric power control of the superconducting magnet has to be elaborated to avoid unnecessary power loss. It is also very important for the AC loss to be as small as possible especially if the magnet is conductively cooled by a cryocooler. Some magnetic refrigerators for room temperature utilized permanent magnet to magnetize their magnetic refrigerants [17-19]. Even though the maximum magnetic field of the permanent magnet is much smaller than that of most superconducting magnets and, therefore, the magnetization intensity is fairly limited, the advantage of using no additional power source is quite an attractive feature.

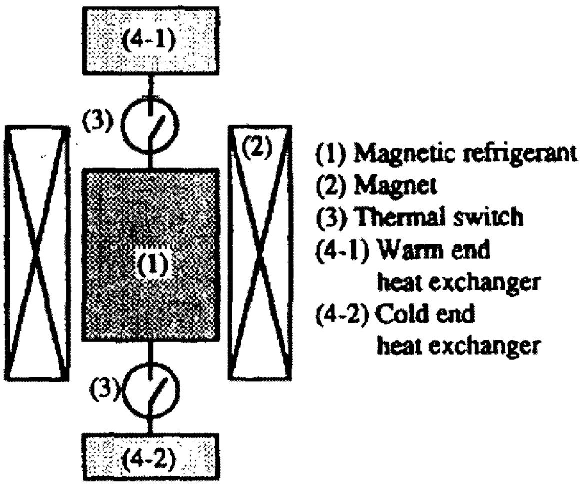


Fig. 2. Key components of typical magnetic refrigerator.

TABLE II.
POTENTIAL MAGNETIC MATERIALS FOR A MAGNETIC REFRIGERATOR.

No.	Substance	T_c *(K)	Characteristic	Ref.
1	$Dy_3Ga_5O_{12}$ (DGG)	0.37	high thermal conductivity, good for Ericsson cycle (2 K ~ 12 K)	[29]
2	$Gd_3Ga_5O_{12}$ (GGG)	0.85	high thermal conductivity, excellent magnetic refrigerant below 10 K	[30]
3	$Gd_3Al_5O_{12}$ (GAG)		high thermal conductivity, difficult to make in the form of single crystal	[29]
4	$Gd_3(Ga_{0.8}Al_{0.2})_5O_{12}$		solid solution of GAG and GGG	[29]
5	$Gd_2(SO_4)_3$	< 1	lighter than GGG, good for temperatures below 1.8 K	[11]
6	$Dy_2Ti_2O_7$	1.35	available in powder form, temperature range (4.2 K~20 K)	[31]
7	$HoPO_4$	1.39	RXO_4** family	[32]
8	$TmVO_4$	2.15	RXO_4** family, high thermal conductivity	[32]
9	$Dy_3Al_5O_{12}$ (DAG)	2.53	high thermal conductivity, better than GGG above 10 K	[33]
10	$DyVO_4$	3.0	mixed with GGG in Ericsson type machine between 2 K and 20 K	[34]
11	$DyPO_4$	3.39	RXO_4** family	[32]
12	$TmAsO_4$	6.0	RXO_4** family, good material in the temperature range 5 to 10 K	[32]
13	$ErNi_2$	6.7	promising material in the wide temperature range below 35 K	[35]
14	$ErAl_2$	11.7	useful for compound material for Ericsson type machine above 15 K	[36]
15	$HoNi_2$	12.3	promising material in the wide temperature range below 35 K	[35]
16	EuS	16.0	promising material in Ericsson type machine above 20 K	[29]
17	$DyNi_2$	19.3	promising material in the wide temperature range below 35 K	[35]
18	$HoAl_2$	26.8	useful compound material for Ericsson type machine above 15 K	[36]
19	$(Ho_{0.5}Dy_{0.5})Al_2$	46	useful compound material for Ericsson type machine above 15 K	[36]
20	$DyAl_2$	55.9	useful for Ericsson type machine between 20 K and 77 K	[29]
21	Ho_5Si_4	76	ferromagnetic rare-earth intermetallic compound	[37]
22	$GdNi_2$	85	promising material in the wide temperature range below 35 K	[35]
23	$(GdEr)_{0.5}Al_2$	96	compound of $GdAl_2$ and $Er_{0.5}Al_2$	[38]
24	Dy_5Si_4	140	ferromagnetic rare-earth intermetallic compound	[37]
25	$GdAl_2$	164	low hysterisis material	[38]
26	$GdAl_{1.9}Ni_{0.1}$	191	ferromagnetic rare-earth intermetallic compound	[37]
27	Gd_3In	213	ferromagnetic rare-earth intermetallic compound	[37]
28	Tb_5Si_4	225	ferromagnetic rare-earth intermetallic compound	[37]
29	Gd_3Al_2	287	ferromagnetic rare-earth intermetallic compound	[39]
30	Gd	293	useful for room temperature heat pump	[37]
31	MnP	298	magnetic material for room temperature heat pump	[39]
32	Gd_5Si_4	336	magnetic material for room temperature heat pump	[39]

* Phase transition temperature; ** Rare earth material, X = V, As or

(3) Thermal switch

A thermal switch is also called as a thermal valve or a heat switch. As mentioned earlier, a magnetic refrigerator requires a one-way heat transfer mechanism between the magnetic refrigerant and its surroundings, which is similar to a check valve in hydraulic system and a diode or an SCR (Silicon Controlled Rectifier) in electrical system. During the adiabatic magnetization or demagnetization processes, the magnetic refrigerant should be thermally isolated from the environment, but it needs to have efficient thermal communication with the warm or cold end heat exchangers during the certain other periods of the cycle. Various types of thermal switch (superconducting, mechanical, and hydraulic) have been explored with extensive research efforts. Superconducting thermal switch utilizes thermal conductivity difference between the superconducting state and the normal state of a material such as lead (Pb). In the superconducting state, a lead valve is "closed" and heat is passed; in the normal state, it is "open." This valve is static and magnetically activated. The disadvantage of this system is the narrow operating temperature range imposed by the valve and the loss of superconductivity at high heat fluxes, making such devices unsuitable for a large refrigeration capacity. Mechanical contact switches have also been explored. Such a switch has an advantage in that there is virtually no heat leakage through it when the contact is eliminated. On the other hand, a serious disadvantage is its dynamic feature and the energy dissipation associated with contact opening or closing. This energy dissipation is usually too large to be tolerated in the temperature region below 0.5 K. The heat pipe or thermosyphon is very useful as a thermal switch or a thermal diode to allow only one-directional heat flow. It is a static promising thermal switch, but limited to certain temperature range for its operation due to its working fluid property.

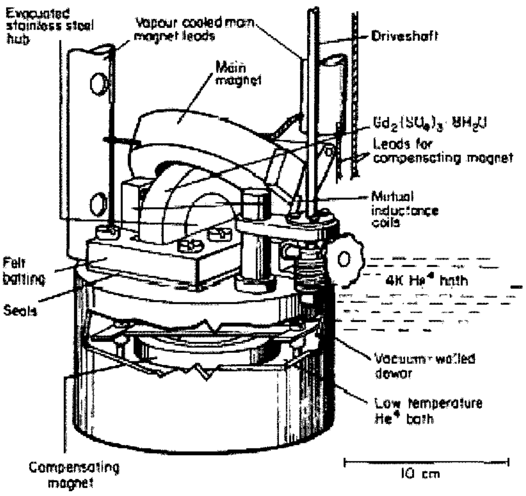
(4) Heat exchanger

Typically a magnetic refrigerator requires two heat exchangers; one at the cold end where it cools down the external cooling load and the other at the warm end where the heat is rejected to the higher temperature environment. Having high thermal effectiveness and minimizing the dead volume between the magnetic refrigerant and the heat exchanger is indispensable where the small magneto caloric effect of the magnetic refrigerant is likely to be negated by an inefficient design of the heat exchanger in practical application. Thermal design of the heat exchanger is especially critical for the case of large temperature span. Additionally, if the heat exchanger is exposed to strong magnetic field variation in cryogenic magnetic refrigerator, its design must minimize parasitic heat generation due to eddy current because the specific heat of the material is small when the temperature is low.

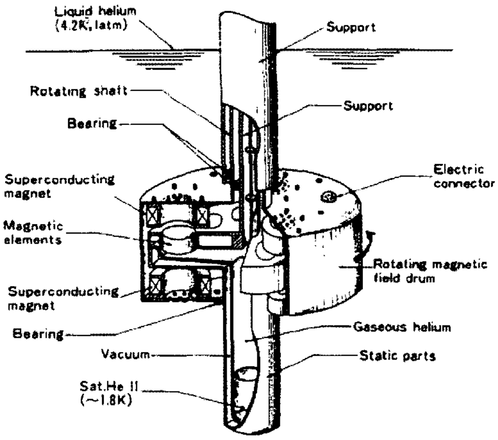
5. CLASSIFICATION OF MAGNETIC RERIGERATOR AND ITS APPLICATION TEMPERATURE RANGE

5.1. Dynamic configuration vs. static configuration

A dynamic magnetic refrigerator involves relative displacement between the magnetic refrigerant and the steady field magnet. Two kinds of common movement are rotating (Fig.3) and reciprocating (Fig. 4). Since the magnetic interaction force is fairly large, a design to reduce the overall force by having multiple magnetic refrigerant beds to operate 180° out of phase is usually applied. A static magnetic refrigerator utilizes a superconducting magnet that provides changing magnetic field to magnetize and demagnetize the magnetic refrigerant without involving any motion of an active component. This is a mechanically reliable system even though the electric power control for the magnet has to be done efficiently.

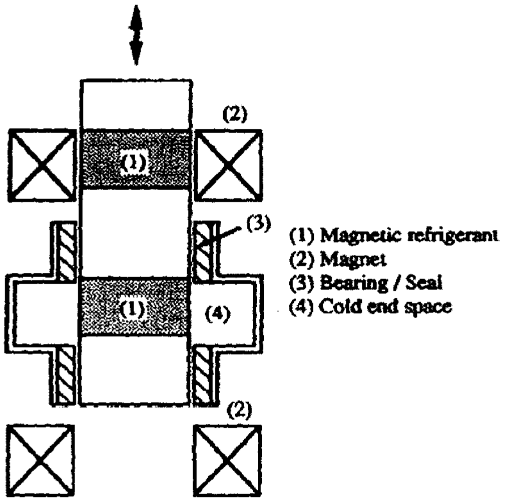


(a) Rotating magnetic refrigerant type (Pratt et al. 1977 [8])

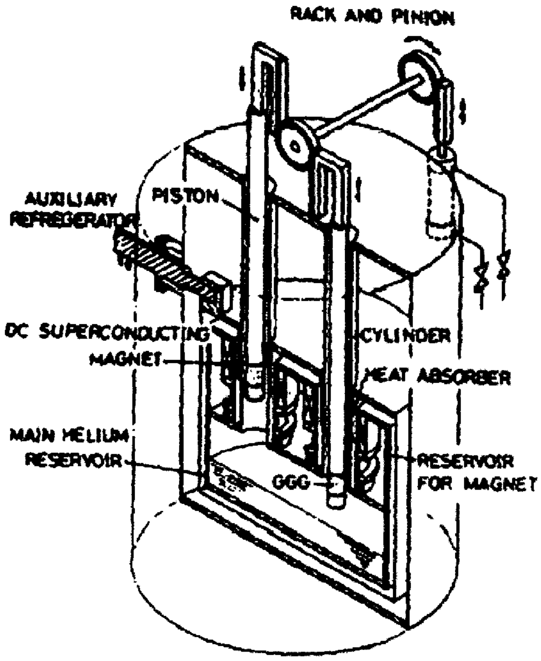


(b) Rotating magnet type (Hakuraku et al. 1986 [40])

Fig. 3. Rotating magnetic refrigerators.

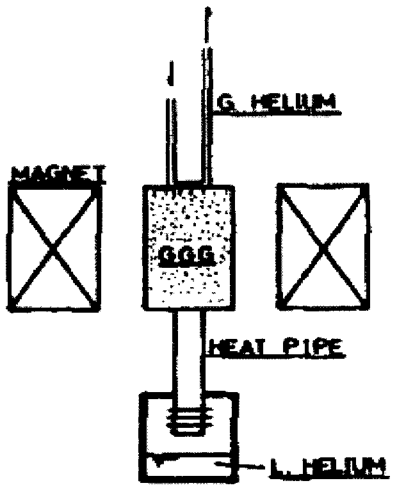


(a) Double acting single column type refrigerator for 1.8 K (Delpuech et al. 1981 [11]

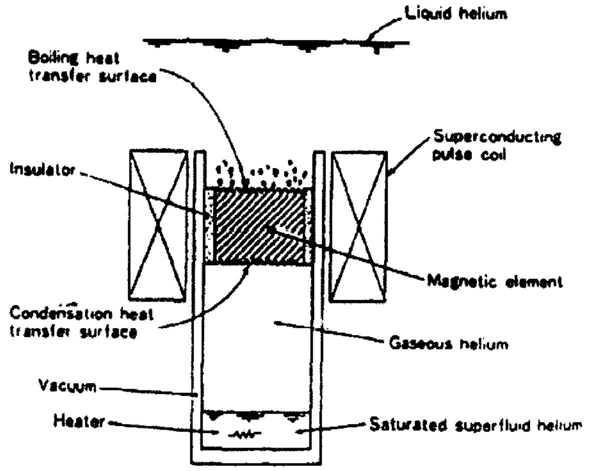


(b) Double acting double column type refrigerator for 4.2 K (Nakagome et al. 1985 [41])

Fig. 4. Reciprocating magnetic refrigerators.



(a) Refrigerator for 4.2 K using heat pipe as thermal switch (Nakagome et al. 1984 [6])



(b) Refrigerator for producing superfluid helium at 1.8 K (Hakuraku et al. 1985 [7])

Fig. 5 Static magnetic refrigerators.

Fig. 5 (a) shows a static magnetic refrigerator developed by Nakagome et al. [6] for liquefying helium. They utilized a static heat pipe as the thermal switch at the cold end. Hakuraku et al. [7] also developed a static refrigeration system to produce superfluid helium as shown in Fig. 5 (b).

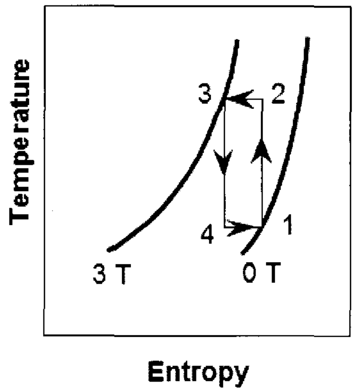
5.2. Simple Carnot cycle vs. regenerative cycle

The simplest magnetic refrigerator is a single Carnot type machine as shown in Fig. 6 (a). This single-cycle has been investigated by many researchers (Barclay et al. [42], 1985, Nakagome et al. [6], 1984, Hakuraku et al. [7], 1985, Numazawa et al. [5], 1993). However, the single Carnot cycle has some basic shortcomings. The magneto-thermodynamic properties of most refrigerants make inherently it difficult to operate over a large temperature span with practical levels of magnetic field.

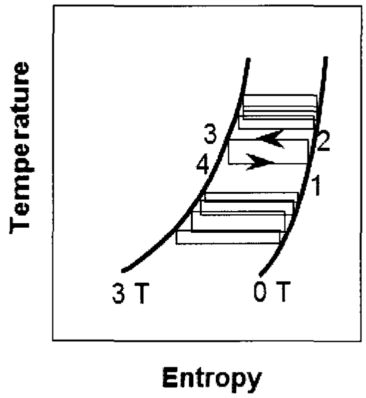
Consequentially, the regenerative (or cascade Carnot refrigeration) cycle, as shown in Fig. 6 (b), is more appropriate than the single Carnot type for applications requiring large temperature spans (Van Geuns [12], 1966, Barclay et al. [43], 1976, Taussig et al. [13], 1986, Jeong et al. [14], 1994). The cascade magnetic Carnot cycle is composed of many independent sub-Carnot cycles by porous magnetic refrigerants along the temperature axis. For the given magnetic field swing that is limited by an accompanied magnet, a magnetic refrigerant is more efficiently utilized by the cascade Carnot cycle than the single one. The amount of heat pumping between the adjacent cycles, however, has to be precisely matched to construct an efficient system with less entropy generation. The magnetic refrigerant in the latter system is often called an AMR (Active Magnetic Regenerator) compared to a passive regenerator [21-24] that is commonly used in most regenerative cryocoolers such as Gifford-McMahon , Stirling, and pulse tube refrigerators. In this case, we consider a porous magnetic refrigerant as a regenerator because its physical configuration is very similar to a conventional regenerator except for the important fact that the heat capacity of the regenerator can be actively controlled by the changing magnetic field. Obviously in the case of usual regenerative magnetic refrigerators, the heat transfer medium normally passes through the magnetic core without its pressure swing. No active hydraulic compression and expansion effect is incorporated in a typical magnetic refrigerator. It is, therefore, a logical way now to modify a regenerative cryocooler utilizing AMR in that the insufficient lattice specific heat at very low temperature can be compensated by active magnetic entropy change [44, 45]. This is a true hybrid technology fusion between hydraulic and magnetic refrigeration.

5.3. Temperature range and its applications

A magnetic refrigerator can be theoretically constructed for any refrigeration temperature if the material as shown in Table II is appropriately selected. The following typical temperature range can be divided according to its specific applications.



(a) Single Carnot cycle



(b) Regenerative (or cascade Carnot) cycle

Fig. 6 Magnetic refrigeration cycles.

(1) Below 1.5 K

In general, far infrared bolometers and X-ray spectrometers used in astrophysics have better performances (signal to noise ratio) as their temperatures are lowered [46]. When they are used in extra terrestrial environment, a cryogenic refrigeration device is often necessary to provide adequate and stable cooling for their operating temperatures. A magnetic refrigerator is especially attractive due to its gravity insensitiveness. Different from a dilution refrigerator, a magnetic refrigerator can operate in a micro-gravity environment like space. Even though the required cooling capacity is as small as 10 μW, precise temperature control is very demanding in this application. An ADR (Adiabatic Demagnetization Refrigerator) system was proposed [47] and researched to cool far infrared bolometers on the multi-band imaging photometer of the Space Infrared Telescope Facility (SIRTF) by using a ferric ammonium alum salt pill.

(2) 1.5 – 4.2 K

The most important refrigeration purpose in this temperature range is to produce superfluid helium which is subsequently utilized for cooling sensitive cryogenic detectors [14, 46] or superconducting magnets. Conventional approach to obtain this temperature range is to pump down liquid helium by a powerful vacuum pump. This vapor-pressure control method is simple and easy, but the vaporized helium is difficult to be recycled. The cooling load for a magnetic refrigerator to cope with varies from 10 mW to a few watts and the most frequently used magnetic refrigerants are GGG ($Gd_3Ga_5O_{12}$) and $Gd_2(SO_4)_3$-$8H_2O$ [8, 11, 14].

(3) 4.2 - 20 K

As the target temperature of a cryogenic refrigerator goes down especially below 10 K, all the regenerative cryocoolers suffer from poor regenerator efficiency. The thermal ineffectiveness of the second stage regenerator may reach above 5 %, which is very detrimental to the whole system performance. One way to overcome this problem is to combine a Joule-Thomson expansion cooler and a regenerative cryocooler such as Gifford-McMahon refrigerator. The other approach is to utilize rare-earth materials such as Er_3Ni or $HoCu_2$ as the regenerator matrix with their high magnetic entropy change. A magnetic refrigerator in this temperature range is to replace Joule-Thomson expansion process or expensive rare-earth regenerator matrix by a more reliable and efficient hybrid mechanical cooler for liquid helium temperature. The cooling capacity ranges from 0.5 to a few watts and again GGG ($Gd_3Ga_5O_{12}$) has been the most common refrigerant material [5, 6, 13] although DAG ($Dy_3Al_5O_{12}$) is also proposed to be useful [5, 33].

(4) 20 – 77 K

77 K is the NBP (Normal Boiling Point) of liquid nitrogen which is readily obtained. A magnetic refrigerator in this temperature range is to serve as a cascade

refrigerator of the upper stage of the 4.2 K magnetic refrigerator or an efficient hydrogen liquefier. In conjunction with emerging hydrogen economy in the 21st century, great attention has been paid to developing more efficient hydrogen liquefaction system these days [26]. Without inherent irreversible process, a magnetic refrigerator can be surely an attractive hydrogen liquefier. The proposed magnetic refrigerants are the combination of ferromagnetic or ferromagnetic materials having wide transition temperature spectrum rather than a single paramagnetic material. The developed magnetic refrigerators using GGG or DGAG have not produced large temperature swing for hydrogen liquefaction system [27, 28]. A layered regenerative magnetic refrigerator using several materials looks inevitable to expand the temperature span.

(5) Near room temperature

A magnetic refrigerator for near room temperature is a promising alternative refrigeration method in that it does not use any environmentally troublesome ozone depleting chemicals such as CFC (Chlorofluorocarbon). It certainly has attracted more interest recently from researchers. From an applications perspective, the market for refrigeration and heat-pump technologies in this regime is vast and is an attractor for technology development. The system with small temperature span can potentially have a high coefficient of performance value. Increases in permanent magnet strengths have made it possible to construct permanent magnet arrays with reasonably sized volumes of free space and flux densities on the order of 1.5 T. Another development, which is important for increasing magnetic refrigeration performance, is the discovery of materials displaying large entropy changes due to field-induced, first-order, phase transformations. The possibility of a magnetic refrigeration device without the need for a separately excited coil magnet combined with the possibility of a larger magneto-caloric effect makes a device more feasible. There are review papers for research of room temperature magnetic refrigeration [48, 49] and the recent IIF-IIR International Conference on Magnetic Refrigeration at Room Temperature[50] in 2005 has compiled the most updated technical contents in this area and, therefore, a good source as the reference.

6. RECENT RESEARCH TRENDS OF MAGNETIC REFRIGERATOR

First, an ADR system is already proven to be a practically effective device either for space application or terrestrial purpose. The system for ultra low temperature range (near 50 mK) has been recently commercialized [51]. In this very low temperature system, a gas-gap or a superconducting thermal switch is mostly used. Currently, more research efforts are focused on efficient system integration such as a better thermal switch or a low-loss compact superconducting magnet. Second, thermodynamically more efficient hydrogen liquefaction systems are being developed to be competitive against a conventional vapor-compression refrigerator around 20 K. An efficient magnetic hydrogen liquefier must be a sure driver for hydrogen economy in the 21st century. Third, room temperature magnetic refrigeration system has drawn continuous attention. Both a permanent magnet and a superconducting magnet have been implemented for continuous room temperature magnetic refrigerators. If there is a breakthrough in developing a magnetic refrigerant with much larger magneto-caloric effect than the current ones, the application of magnetic refrigeration technology will be greatly accepted. In developing both hydrogen liquefaction and room temperature systems, the layered structure of the magnetic refrigerant for AMR is applied to maximize the magneto-caloric effect of the materials at different temperature range. Fourth, the magnetically augmented regeneration technology is incorporated in a regenerative cryocooler [44, 45]. Since the magnetic refrigerator has usually operated in low temperature ranges (< 4.2 K) with a small temperature span, it has required an additional cooling mechanism for its warm end reservoir. A reliable Gifford-McMahon cryocooler has been one practical way. This cascade connection of magnetic refrigerator and mechanical gas cryocooler is called *"the external combination"*. On the other hand, *"the internal combination"* between magnetic and gas refrigerators is also possible using both hydraulic and magnetic compression/expansion effects. Probably this is one of the most sophisticated hybrid refrigerator technologies to be developed. AMR can assist a conventional gas compression cycle with higher regenerator effectiveness especially at low temperature below 10 K.

7. SUMMARY

This paper reviews magnetic refrigeration technology; historical developments, fundamental concepts of magneto-thermodynamics, key components, application classification, and recent research trends. It is the technology of utilizing strong magnetic field to obtain low temperature. Depending on the magnetic refrigerant, the magnetic refrigerator can be not only useful for reaching sub-Kelvin temperature where no gas expansion can create cooling effect but also applicable to much higher temperature range such as liquid hydrogen temperature or even near room temperature. The key component of the refrigerator is a novel magnetic refrigerant material which must possess sufficiently large magneto-caloric effect. With this, a pseudo-Carnot magnetic refrigeration cycle can cover reasonably large temperature span. Otherwise, a regenerative concept should be employed to expand the temperature span of the refrigeration cycle. Magnetic refrigeration is composed of static reversible magnetization and demagnetization processes without irreversibility issues associated with mechanical or hydraulic movement. It is an inherently efficient heat pumping method and, therefore, can have a higher thermodynamic coefficient of performance than that of gas refrigeration. In order for the magnetic refrigerator to be a practically viable engineering technology, however, we have to be very careful not to generate excessive entropy in the auxiliary components including the heat exchangers and the magnet as well as the magnetic refrigerant core itself.

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