

A Review on Magnetic Refrigeration at Room Temperature

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ABSTRACT: The objective of the paper is to study the Magnetic Refrigeration which makes use of solid materials such as Gadolinium silicon compounds as the refrigerant. These materials illustrate the unique property known as magneto caloric effect, where there is an increase or decrease in temperature when magnetized or demagnetized respectively. This effect was observed many years ago and was used for cooling to near absolute zero temperature. In the recent times materials are being developed in which enough temperature and entropy change is produced which makes them useful for a wide range temperature applications. Magnetic refrigeration is an emerging technology that utilizes this magneto-caloric effect found in solid state to produce a refrigeration effect. The combination of solid-state refrigerants, water based heat transfer fluids and its high efficiency unlike the traditional methods lead to environmentally desirable products with minimal contribution to global warming. If current research efforts are successful, within a few years, you may find compressors and evaporators only in the history books. However, so far a few prototype refrigeration machines are presented as there are quite a few technological and scientific challenges need to be overcome. Among the numerous applications of refrigeration technology, air conditioning applications contributing largest gross cooling power and using large amount of quantity of electric energy.

KEYWORDS: Magnetic Refrigeration, Refrigeration using Magnetic field, Magneto-caloric effect

I.INTRODUCTION

Modern society largely depends on traditional refrigeration methods like vapour compression cycles and vapour absorption cycle. The vapour compression refrigerators have been commercially used for refrigeration applications which are based on gas compression and expansion and are not very efficient because the refrigeration accounts for 25% of residential and 15% of commercial power consumption. Moreover, using gases such as chlorofluorocarbons hydrochlorofluorocarbons (CFCs and HCFCs) have adverse effects on our environment. Recently, the developments of new technologies – such as magnetic refrigeration along with the thermoelectric refrigeration have brought an alternative to the conventional gas compression technique.

The magnetic refrigeration at room temperature is an emerging technology that has drawn the interest of researchers around the world. Magnetic refrigeration is a cooling technology based on the magneto-caloric effect discovered more than 130 years ago. This method can be used to attain the temperatures near 0 K, as well as the ranges used in common refrigerators, depending on the design of the system. The effect was first observed by the German physicist Emil Warburg in the year 1881, and the basic principle was then suggested by Debye (1926) and Giauque (1927). The first working magnetic refrigerators were constructed by many people from 1933. Magnetic refrigeration was the first method developed for cooling below about 0.3K

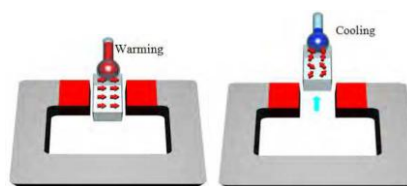


Fig.1.1 Magneto Caloric Effect

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When a magneto-caloric material is subjected to a strong magnetic field (measured in Tesla, T), the electrons present in the material are forced into alignment with the magnetic field. That is, the magnetic field performs work to align the electron spins into thermodynamically lower energy state. The energy released during the process causes the temperature of the material to rise. When the magnetic field is lowered, the electron spins return to their more random and zig-zag motion, higher energy state, absorbing heat from the material and causing the temperature to fall.

Eventually, this technology could be used to develop a standard refrigerator that can be used for household purposes. The use of magnetic refrigeration has the potential to reduce operating and maintenance costs with higher energy efficiencies.

II. WORKING PRINCIPLE

The Magnetic Refrigeration works on the principle of Magneto-Calorific Effect. It is basically a thermodynamic effect caused due to the changing magnetic field, hence called as magneto thermodynamic phenomenon. The Magneto caloric effect (MCE, from magnet and calorie) is a magneto-thermodynamic phenomenon in which a reversible change in temperature of a suitable material is caused by exposing the material to a changing magnetic field. This is also known as adiabatic demagnetization by some physicists, because of its application in the process to cause the temperature drop. In that part of the overall refrigeration process, a decrease in the strength of an externally applied magnetic field allows the magnetic domains of a Chosen (magneto caloric) material to become disoriented from the magnetic field by the distressing action of the thermal energy (phonons) present in the material. If the material is isolated so that no energy exchange is allowed to between the material and its surrounding i.e (dQ=0 an adiabatic process), the temperature drop takes place as the domains absorb the thermal energy to perform their reorientation.

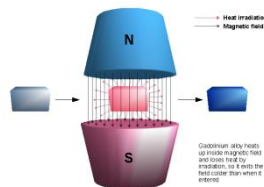


Fig. 2.1. The Magneto Calorific Effect

When the magneto-caloric material is subjected the magnetic field, the magnetic moments of soft ferromagnetic materials get aligned, making the material more ordered. Hence the material liberates more heat and which results in the decrease of their magnetic entropy. But, when the magnetic material subjected to the magnetic field is reduced isothermally, the magnetic moments become disoriented, due to which the material absorbs heat and consequently their magnetic entropy increases.

The magnetic entropy change that takes place due to the magneto-caloric effect can be expressed in the form of equation as below

$$\partial S = \mu \int_{H_i}^{H_f} \left(\frac{dM}{dT}\right) dH \quad (1)$$

While the adiabatic temperature change can be given by the expression as shown below

$$\partial T_{ad} = -\mu \int_{H_i}^{H_f} \left[\frac{T}{C}\right] \left(\frac{dM}{dT}\right) dH \quad (2)$$

Where μ is the permeability of the vacuum,
 H_i and H_f are the initial and final magnetic field strength respectively
 C is the heat capacity at constant magnetic field
 dS is the change in Entropy

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∂T_{ad} - Change in adiabatic temperature

$\frac{dM}{dT}$ - Change in Magnetisation with respect to temperature

Now given the two equations for change in entropy and change in adiabatic temperature, refrigeration capacity for a magnetic refrigerator, which helps in analysing how much heat is actually transferred in one refrigeration cycle.

$$Q = \int_{T_i}^{T_f} dS \, dT \quad (3)$$

From the above equations we can conclude that magneto-caloric effect can be enhanced by applying a large field, using a magnet and small heat capacity, using a magnet with a large change in magnetization vs temperature, at a constant magnetic field.

One of the most notable examples of the magneto caloric effect is in the chemical element gadolinium and some of its alloys. Gadolinium's temperature is observed to increase when it enters certain magnetic fields. When it leaves the magnetic field, the temperature drops back to normal. The effect is considerably stronger for the gadolinium alloy $Gd_5(Si_2Ge_2)$. Praseodymium alloyed with nickel ($PrNi_2$) has such a strong magneto caloric effect that it has allowed scientists to approach within one thousandth of a degree of absolute zero. Magnetic Refrigeration is also called as **Adiabatic Magnetization**.

III. THERMODYNAMIC CYCLE

The basic thermodynamic cycle of the magnetic refrigerator is Brayton Cycle, which operates between two adiabatic and two isomagnetic field lines. The working material is the refrigerant, and starts in thermal equilibrium with the refrigerated environment.

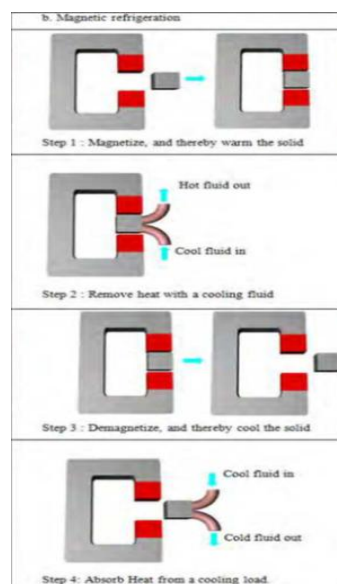


Fig.3.1. Thermodynamic processes in magnetic refrigeration

1. Adiabatic magnetization: A magneto caloric material when placed in an insulated environment ($Q=0$) and external magnetic field is increased ($+H$) it causes the magnetic dipoles of the atoms to align and thereby decreasing the material's magnetic entropy and heat capacity. Since overall energy is not lost during this process, hence the total entropy also does not change, the net result is that the object heats up ($T + \Delta T_{ad}$).

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2. Isomagnetic enthalpy transfer: The magnetic field is held constant during this process ($H=0$) and the heat added during the adiabatic magnetization is then removed ($-Q$) by a fluid or gaseous substance. to prevent the dipoles from reabsorbing the heat. Once completely cooled, the magneto-caloric substance and the coolant are separated.
3. Adiabatic demagnetization: The substance is returned to another adiabatic process ($Q=0$) and hence the total entropy remains constant. However, this time the magnetic field is reduced, the thermal energy causes the magnetic moments to overcome the field, and thus the sample cools, *i.e.*, an adiabatic temperature change. Energy (and entropy) transfers from thermal entropy to magnetic entropy (disorder of the magnetic dipoles).
4. Isomagnetic entropic transfer: The magnetic field is held constant to prevent the material from heating back up. The material is placed in thermal contact with the environment being refrigerated. Because the working material is cooler than the refrigerated environment (by design), heat energy migrates into the working material ($+Q$).

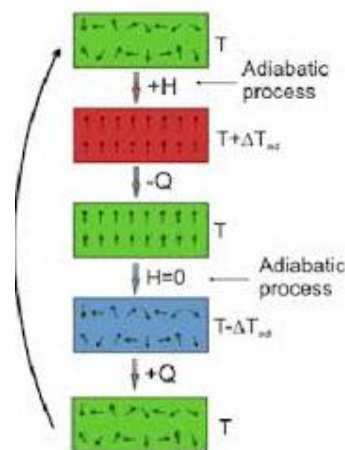


Fig.3.2. Atomic distribution of various thermodynamic processes in magnetic refrigeration

The processes involved in the magnetic refrigeration can be represented using the T-S diagram of the Brayton cycle as shown below (the cycle involves four processes which already discussed)

- 1-2- Adiabatic Magnetization
- 2-3. Isomagnetic Enthalpy Transfer
- 3-4. Adiabatic Demagnetization
- 4-1. Isomagnetic Enthalpy transfer

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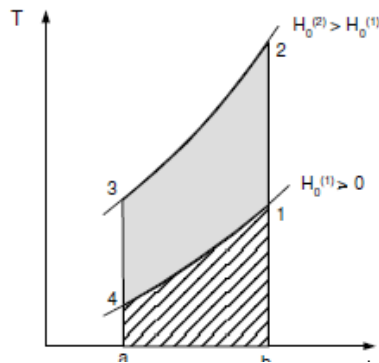


Fig.3.3. T-S diagram for Magneto-caloric Cycle.

IV. TYPES OF MAGNETIC REFRIGERATORS

The four basic thermodynamic processes of the Magnetic refrigeration are most simply realized by the machines as described above. Now the magneto caloric effect was applied in two different ways giving rise to two different types of refrigerators, Linear or axial and Rotary refrigerators. Linear or axial refrigerators was described in the patent of the University Of Applied Sciences Of Western Switzerland (Kitanovskiet *al.*, 2004), whereas second recently deposited patent idea describes a machine of a radial or rotary type of refrigerator. A first step is the magnetization of a porous solid magneto caloric structure in a magnetic field, followed by a simultaneous heating up of the material (Refer A in the figure). By a fluid flow this structure is cooled and after that it turns out of the magnetic field and shows demagnetization process (Refer B in figure). Here the magneto caloric alloy becomes cold and is heated by a fluid flow, which preferable has the opposite direction to the first flow. If the hot fluid on side is used its an heat pump application, if the cold fluid is applied then the machine is a cooler or a refrigerator. The axial machine has the advantage of constant axial fluid velocity, while the rotary machine allows the magnet assembly to be placed in the preferable positions.

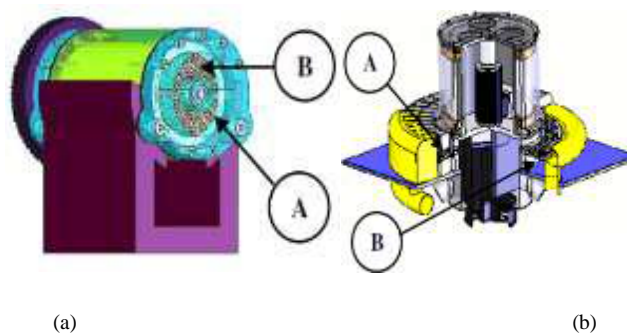


Fig 4.2. Types of Refrigerators (a) Linear or Axial Refrigerator (b) Rotary refrigerator

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V. MATERIAL COMPONENTS OR CONSTRUCTION

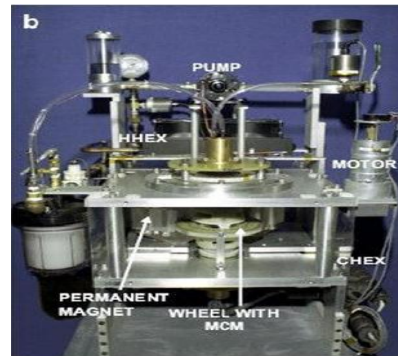


Fig. 5.1.Components or Parts of Magnetic Refrigerator

1. Magnets- Magnets are the main functioning elements of the magnetic refrigeration. Magnets are the one that provide the magnetic field to the material which provide the refrigeration effect i.e. they lose the heat to the surrounding and gain heat from the space to be cooled respectively. The magnets used are usually made of ceramic or ferrite.
2. Hot Heat Exchanger- Here, the heat transfer is taking place between the magneto-caloric material and the heat exchanger, The heat exchanger gains the heat from the material used and release it into the surrounding. It makes the transfer of heat much effective.
3. Cold Heat Exchanger- The working of the cold heat exchanger is similar as compared to the hot heat exchanger except that it absorbs the heat from the space to be cooled and gives it to the magnetic material. It helps to make the absorption of heat more effective.
4. Drive- Drive provides the right rotation to the heat to rightly handle it. Due to this, heat flows in the right desired direction.
5. Magneto caloric Wheel- It forms as the basic structure of the whole device and it turns through the field of a permanent magnet. The wheel is packed with spherical particles of the magneto-caloric material like Gadolinium, which acts as refrigerant. It joins both the magnets to work orderly
6. One of the most important components in the process is magnetic refrigerant. Pure gadolinium may be regarded as being the ideal substance for magnetic refrigeration, just as the ideal gas is for conventional refrigeration. Various other compounds are used as the magnetic refrigerant components as the pure Gadolinium is very rare and cannot be used in ambient temperature due to its other properties. The details of the magnetic refrigerants are discussed in the next section.

VI. MAGNETIC REFRIGERANTS

As already discussed, Pure gadolinium may be regarded as being the ideal substance for magnetic refrigeration, just like the ideal gas is for conventional refrigeration. But just as conventional systems are practically cannot be operated with ideal gases, magnetic refrigerators using pure gadolinium is also not possible and it performs better with specially designed alloys. Below is the list of the promising categories of magneto-caloric materials for application in magnetic refrigerators

1. Gadolinium- Silicon- Germanium Compounds
2. Binary and ternary intermetallic compounds
3. Manganites
4. Lanthanum iron based compounds etc

Gadolinium, a rare earth metal and exhibits one of the largest known magneto-caloric effects. It was used as the refrigerant in many of the early magnetic refrigeration systems. The problem with using pure gadolinium as the

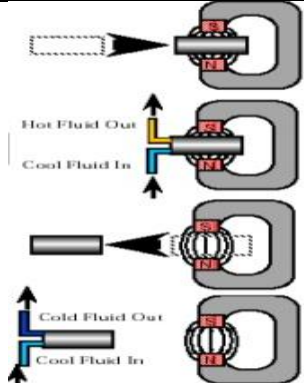
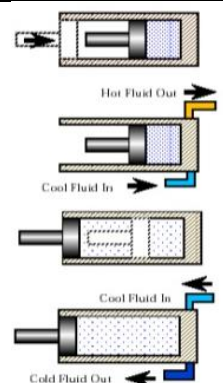
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Refrigerant material is that it does not exhibit a strong magneto-caloric effect at room temperature, where the usual applications of the effect exist. However, it has been discovered that arc-melted alloys of gadolinium, silicon, and germanium are quite efficient at room temperature. Gd-Si-Ge alloys are all considerably large in the presence of a 5 T magnetic field and most of those Curie temperatures are in the room temperature range. Therefore, this series of alloys meet the requirements of room temperature magnetic Refrigeration. However, many urgent problems such as easy oxidation, hard preparation, and high price, need to be settled before they are applied in room temperature magnetic refrigeration.

VII. COMPARISONS

	Magnetic Refrigeration	Conventional Refrigeration
Step 1	Magnetize the Solid thereby Increasing the temperature	Compressing the gas and hence increasing the temperature
Step 2	Removing the heat from the hot fluid using the Heat Exchanger	Removing the heat with the cooling fluid
Step 3	Demagnetizing adiabatically and cooling the solid i.e reducing the temperature	Expansion of gas resulting in the cooling process
Step 4	Absorb heat from the cooling load	Absorb the heat from the cooling load
The Schematic stepwise representation of the four steps in refrigeration		

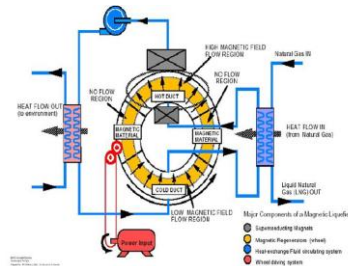
VIII. APPLICATIONS

6.1. A rotary AMR liquefier :- The Cryo-fuel Systems Group is developing an Active magnetic regenerator, an apparatus having a regenerator bed of material exhibiting the magneto-caloric effect for the purpose of liquefying natural gas. A rotary configuration is used to move magnetic material into and out of a superconducting magnet. This technology can also be extended to the liquefaction of hydrogen.

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Other Future Applications.

In general, at the present stage of the development of magnetic refrigerators with permanent magnets, hardly any freezing applications are feasible. These results, because large temperature spans occur between the heat source and the heat sink. Such are used for freezing, e.g. in cooling plants in the food industry or in large marine freezing applications. Some of the future applications are:

1. Magnetic household refrigeration appliances
2. Magnetic cooling and air conditioning in buildings and houses
3. Central cooling system
4. Refrigeration in medicine
5. Cooling in food industry and storage
6. Cooling in transportation
7. Cooling of electronics

IX. MERITS

1. Environmental friendly- Refrigerant used is solid and non-volatile and hence eliminating Green House effect. Conventional refrigerator use refrigerant that contains CFC or HCFC, which have been linked to Ozone depletion and global warming. Some refrigerant like ammonia are toxic and inflammable.
2. Low running and operating cost- There is no compressor in magnetic refrigerator, which is most inefficient and costlier part. This leads in less energy consumption and hence low running cost.
3. Higher efficiency- Because it eliminates the need to expand and compressed the liquid, magnetic refrigerator consume less energy and can operate at 60% efficiency.
4. Wide temperature span- Operating temperature of magnetic refrigerator can easily be changed over a wide range from about 30 k to 290 k without losing the magneto-caloric effect.
5. Reliability- High energy density and more compact device, less moving parts as compared to traditional system hence more reliable.
6. Quiet operation- This refrigerator unit is substantially quiet than traditional refrigeration system.
7. Compactness: - It is possible to achieve high energy density compact device. It is due to the reason that in case of magnetic refrigeration the working substance is a solid material (say gadolinium) and not a gas as in case of vapor compression cycles.

X. DEMERITS

1. The initial investment is very high when compared to conventional refrigeration.
2. The magneto caloric materials are rare earth materials hence their availability also adds up to become a disadvantage. These materials need to be developed to allow larger frequencies of rectilinear and rotary magnetic refrigerators.
3. Protection of electronic components from magnetic fields. But it must be noted that they are static, of short range and may be shielded

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4. Permanent magnets have limited field strength. While, Electromagnets and superconducting magnets are very expensive.
5. Temperature changes are limited. Multi-stage machines lose efficiency through the heat transfer between the stages.
6. Moving machines need high precision to avoid magnetic field reduction due to gaps between the magnets and the magneto caloric material.

XI. CONCLUSION

The list of possible applications involves all domains of refrigeration, heat pump technology and power conversion. But there are two conditions which limits the applications of the technology in its current state. The first is the temperature span. As the difference between the upper and lower temperature levels is large, the number of stages also becomes also large and is practically not economic. The second condition is regarding the stability of the running conditions. Because the Magneto-caloric effect is limited to a domain around the Curie temperature where the continuous phase transition occurs, it is difficult to operate magnetic refrigerating machines under highly fluctuating conditions.

More or less stable temperature levels are required. If we say future perspectives of room temperature Magnetic Refrigeration; It can be seen from the earlier Description that main progresses have been made in America. However, with the continual phasic progresses of Room temperature magnetic refrigeration, the whole world Has accelerated in the research. Nevertheless, it is notable that main work is concentrated On investigations of magnetic materials, lack of Experimental explorations of magnetic refrigerator. From the former results achieved by researchers, it can be seen. At the end of this study we can say

1. It is a technology that has proven to be environmentally safe.
2. In order to make the magnetic refrigerator commercially Viable, scientists need to identify how to achieve larger temperature changes with minimum stages and also permanent magnets that can produce strong magnetic fields.
3. There are still some thermal and magnetic hysteresis problems that needs to be solved for the materials to be used for general applications.
4. Magnetic materials available for room Temperature magnetic refrigeration are mainly Gd, Gdsige alloys, mn as-like materials, perovskite like Materials,
5. The simplicity of the design of the refrigeration operation makes it even more desirable.

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