

A REVIEW ON MAGNETIC REFRIGERATION - A BOON FOR FUTURE GENERATIONS

Abstract

In conventional cooling process called refrigeration, the refrigerant (cooling liquid) evaporates at low pressure and temperature and extracts the heat from the medium that have to be cooled. But in magnetic refrigeration, a special material called magneto-caloric material is used for cooling. Magnetic refrigeration is a freezing process build on magneto-caloric effect(MCE). This phenomenon is noticed long back and this effect is used for refrigeration to achieve very low temperatures such as near absolute zero temperatures. In magneto-caloric effect the temperature of the magneto-caloric material changes when it is magnetized and de magnetized. The most important criteria in MCE is that, when magneto-caloric materials are magnetized and de magnetized the variation in temperatures are achieved at faster rate, repeatedly and reversibly with minimum loss in energy. In conventional method of cooling it needs a compressor and liquid filled in it which has high cost. To operate they require lot of power and the gases used in the refrigeration are hazardous to environment. When we compare between magnetic refrigeration technology and compressor based refrigeration there are many advantages for former, like getting low cost bills, easily available magneto-caloric materials and no harmful environmental impacts. The main aim of this chapter is to study about magnetic refrigeration by using solid materials.

Keywords: Magneto-caloric effect, adiabatic changes, fluid de-magnetization

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I. INTRODUCTION

Magnetic refrigeration is a new technology developed over conventional gas compression technique. Till date the widely used refrigeration technique is traditional compressor based refrigeration. It uses Chloro Fluoro Carbons (CFC) or Hydro Chloro Fluoro Carbons (HCFC) as compressor liquids which have an adverse effect on our environment. They have good cooling capability but are not environment friendly. Release of these gases are very harmful and are responsible for ozone depletion and causing global warming [1][2].

Magnetic refrigeration is a well-established cooling technique that is proposed and is first implemented in the 1930. This phenomenon is used to generate extremely low temperatures in the order of sub-Kelvin temperatures by using the effect of magnetic field on the entropy of a system [3]. In magnetic refrigeration process we use magneto-caloric effect to lower the temperatures of the system. At first, suitable magneto-caloric material which is in thermal equilibrium with the surroundings is selected and magnetic field is applied. It is observed that as the magnetic field is applied the temperature of magnetic material increases. This increase in temperature is due to the ordered orientation of magnetic domains in the external field direction. As the temperature of magneto-caloric material is more it transfers heat to its surroundings. When the strength of magnetic field decreases, the domains orient randomly. To bring this reorientation of domains back the applied magnetic field carries out the work of ordering the domains in their lower energy states and as a result the temperature drops giving the cooling effect which is used in refrigeration process. This phenomenon is used to get reasonably less temperatures in the order of 0.0001 K. The temperature ranges achieved by this new solid cooling systems appears to be perfect for the cooling and refrigeration process.

II. MAGNETO-CALORIC MATERIALS

The existing magnetic coolants emit harmful gases, efficiency of cooling is less with more power bills and creates a lot of noise in operation mode. These drawbacks of this process are being addressed by a latest group of magnetic refrigerant materials for room-temperature applications. These materials have proved to be more advantageous when compared to the already existing magnetic coolants. They show large magneto-caloric effect (MCE) along with first order magnetic phase transition. These magnetic refrigerant materials are called as magneto-caloric materials. Best examples of such materials are Gadolinium (Gd)[4], Gd-Si-Ge system[5], Lanthanum-iron-silicon (LaFeSi), Iron-phosphorus (Fe_2P) alloys etc. Few magneto-caloric refrigerators are designed which can work near room temperature. Gadolinium (Gd) is well suited for this purpose as its Curie temperature is near to room temperature and possess high magnetic moment. But, rare earth metal products based on Gd have high material cost and availability of it is scarce. Therefore, manufacturing of novel magneto-caloric materials having less cost and wide availability is an essential requirement for introducing this technology in the market.

- 1. Types of Magneto-Caloric Materials:** Magneto-caloric materials are broadly classified into two types based on the order of magnetic transition. They are, FOMT (First Order Magnetic Transition) and SOMT (Second Order Magnetic Transition).

2. FOMT (First Order Magnetic Transition)

- The graph between magnetization and applied magnetic field strength is discontinuous in first order magnetic transition materials.
- i.e., In FOMT's the first order derivative of Gibbs free energy shows discontinuity.
- Ordering of magnetic dipoles is observed in FOMT materials
- Latent heat is released in these materials.
- FOMT's show large adiabatic temperature variations when compared to SOMT.
- Hysteresis losses are high in FOMT's.
- Upon either magnetization or demagnetization, FOMT's go through large volume changes and develop cracks as they are brittle in nature.
- FOMT materials experience a coupled magnetic and crystallographic phase transition. i.e., when magnetic field is applied on the material, the magnetic state change from paramagnetic / antiferromagnetic to ferromagnetic with change in structure or a phase volume discontinuity without change in its crystallography.
- For example, MnAs[6] compound is a FOMT having curie temperature (T_C) $\sim$ 220 K to 318 K. It is noticed that MnFeP_{0.45}As_{0.55} having $T_C = 296$ K undergoes first order transition from paramagnetic to ferromagnetic phase.
- The giant magneto-caloric effect in FOMT materials is the algebraic sum of the magnetic entropy-driven process (magnetic entropy change ΔS_M) and difference in the entropies of two crystallographic modifications (structural entropy change ΔS_{st}).
- On a large extent thermal conductivity of FOMT is lesser than SOMT.
- FOMT's are costlier than SOMT's.

3. SOMT (Second Order Magnetic Transition):

- In SOMT, magnetic susceptibility with respect to applied field changes discontinuously.
- SOMT is continuous in first derivative, but discontinuous in second derivative of Gibbs free energy.
- When magnetic field is applied to SOMT material, its magnetic state change from a paramagnet to either a ferromagnet, ferrimagnet or antiferromagnet. The changes in (ΔT_{ad}) or (ΔS_M) are related to $(\partial M / \partial T)_H$ parameter. When $(\partial M / \partial T)_H$ becomes maximum MCE also becomes maximum around the Curie temperature, in ferromagnetic material or nearer to absolute zero in paramagnetic material.
- There are less adiabatic temperature variations in SOMT's than FOMT's.
- There are no structure changes during magnetization or demagnetization and the instantaneous temperature changes are found in the SOMT materials.
- Hysteresis losses are insignificant.
- Upon either magnetization or demagnetization, SOMT's do not undergo volume changes as they are not brittle. There is a continuous flow of heat transfer and results in increased cooling effect.
- Gadolinium is a best example for SOMT. Gd is having T_C at 294 K and undergoes paramagnetic to ferromagnetic second order phase transition.
- Thermal conductivity of SOMT's is significantly higher than FOMT's.

- 4. Magnetic Refrigeration at Room Temperature:** First material that can work at room temperature for magnetic refrigeration without need of super conducting magnet or liquid helium is $\text{Gd}_5\text{Si}_2\text{Ge}_2$ [7] alloy (gadolinium by adding silicon and germanium). Magnetic refrigerator possess a wheel that contains sections filled with gadolinium alloy. This wheel revolves around a highly powered rare earth permanent magnet and passes through a gap in the magnet at a precise point where magnetic field is concentrated. After entering the field, a second stream of water is cooled by the gadolinium alloy. Therefore, it can be concluded that magnetic refrigeration may be easily achieved at room temperature in near future. This alloy reduce the technology cost considerably and achieve very low temperatures by adiabatic demagnetization.

Comparison between magnetic cooling and conventional vapor compression refrigeration:
In Figure 1, the terms are defined below,

$H \rightarrow$ applied magnetic field intensity

$+P \rightarrow$ increase of pressure

$+\Delta T_{ad} \rightarrow$ increase in adiabatic temperature

$-Q \rightarrow$ heat lost to condenser

$-P \rightarrow$ decrease of pressure

$-\Delta T_{ad} \rightarrow$ decrease of temperature ($H=0$ adiabatic process)

$+Q \rightarrow$ cooling effect

Magnetic cooling cycle process is same to that of vapor compression technique[8]. In magnetic cooling, strength of magnetic field is alternately increased and decreased instead of increasing and decreasing the pressure of the refrigerant.

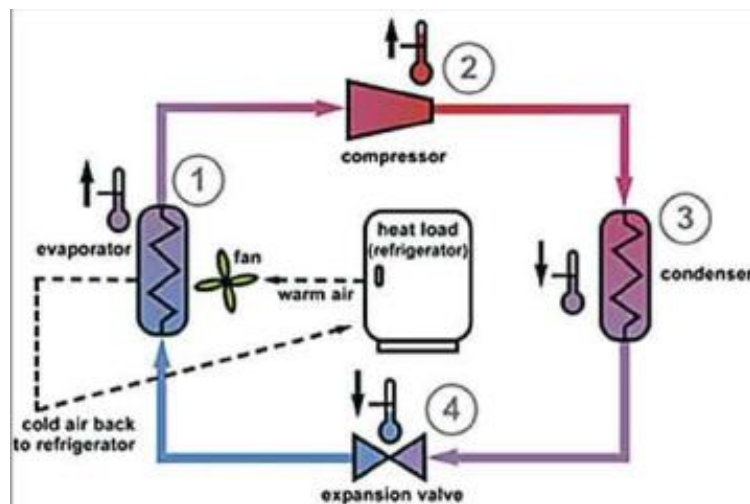


Figure 1: Vapour compression refrigeration cycle.

The above figure shows the conventional vapor compression refrigeration cycle which uses the phase changing property of refrigerant, such as “Freon”, to dissipate the heat from lower temperature to higher temperature. Fig.2 depicts the magnetic refrigeration cycle, which works on the principle of adiabatic magnetization and demagnetization to obtain cooling in magneto caloric material. It has been established that for the same amount of cooling obtained magnetic refrigeration consumes 20 % less energy than vapor compression cycle[9].

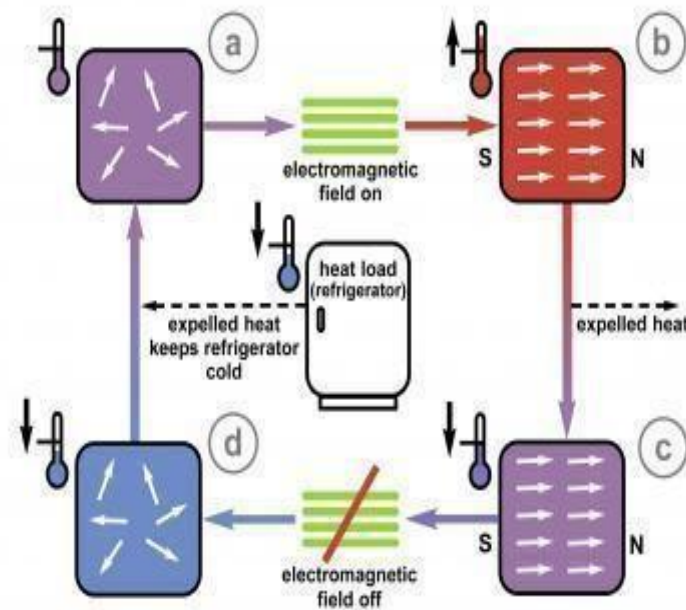


Figure 2: Adiabatic magnetization and adiabatic demagnetization

The magnetic refrigeration or adiabatic demagnetization refrigerator (ADR)[10] is achieved by the following four steps and is shown in fig.3 below:

- First, the fluid is at cold temperature T_c , with no flow. In thermally insulated condition, an intense magnetic field is applied on the magnetization material (refrigerant). This forces the magnetic dipoles to align, releasing heat energy which results in the raise of its temperature.
- Sustaining the applied field, the fluid is circulated along the regenerator. It absorbs heat from the material and transports it to the heat exchanger till it is above the heat rejection temperature (T_h).
- While the refrigerant remains thermally insulated in the magnetized condition, the magnetic field is removed in absence of the fluid flow. Disordering causes an endothermic reaction, hence temperature is decreased below that of the heat sink.
- The fluid is circulated continuously and repeatedly so that it is cooled to desired temperature as in conventional air conditioning system. In this process refrigeration is done.
- In order to obtain continuous cooling the above four steps are repeated many times.

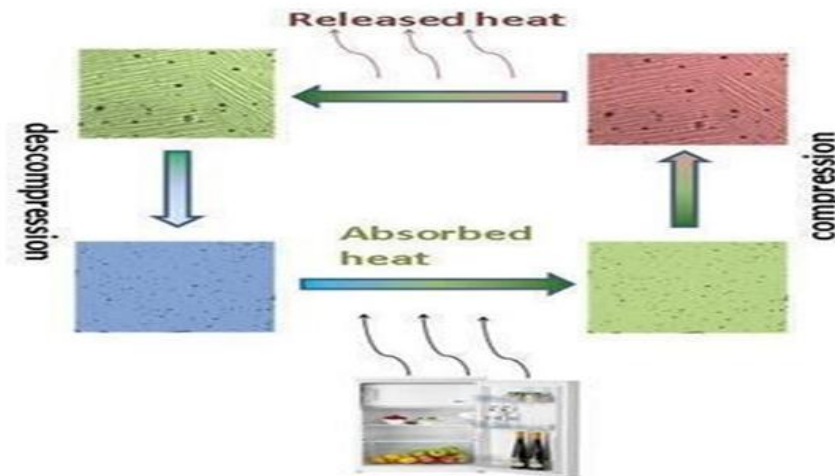


Figure 3: Adiabatic Demagnetization Refrigerator (ADR)

5. Advantages and Disadvantages of Magnetic Refrigeration

- This is safe, durable and simple system. But it is bulky and heavy.
- System running cost is less but by increasing the adiabatic temperature cooling span decreases. Implementing this system is a novel challenge.
- Power consumption reduces by 20 to 30% and it is found to be more efficient. Low temperature is achieved on magnetization as well as by demagnetization.
- By opting this technology global warming and ozone depletion can be avoided. Solid state refrigeration is eco-friendly but require strong magnets which are costly.
- No leakage or contamination of the refrigerant is observed. But, magneto-caloric materials are very expensive.
- It needs very less maintenance as there are no moving parts. Efficiency of magnetic cooling system is dependent on oscillations of magnetic field.
- This method is cost effective and disposal of such system will be simple.
- Magnetic refrigeration is better achieved near curie temperature. It is best suited for comfort air conditioning application if curie temperature of MCE is around 20 °C.
- It can be concluded that it is a boon for future generations because of the inherent advantage the magnetic refrigeration possess in comparison with the conventional vapor compression refrigeration system.

6. Challenges in Magnetic Refrigeration: Although magnetic refrigeration technology is promising, it is not yet ready for the market. The current developments are not fully mature to bring this technology for commercial usage. Companies like, cool-tech application, next pac etc. are to rule this field by working on heat pump applications. Cool-tech application produced 150 -700 w pump as part of refrigeration system and its first test is carried out at end users site in 2015 at supermarkets . At Cambridge University, lot of research is being carried out on magnetic refrigeration. Multinationals companies like Whirlpool, Electrolux, GE Appliances, Samsung etc. are working on similar technologies. Using apt materials or by reducing the contents of MCE shall increase the feasibility of this technology. Production and fabrication process of MCE materials is not optimized and their production cost is still high. To reduce the cost, development of prototypes for various specific applications are to be carried out. Initially

few products should be developed and supplied in the market and their success need to be checked. But still there are lots of challenges that needed to be addressed before large scale application of magnetic refrigeration. The attainable applications of magnetic refrigeration involves all the domains of refrigeration, like heat pump technology, power conversion etc. The first issue to be addressed is temperature span. It is found that the difference between the upper and lower temperature level is large. The number of stages are large which is practically not economic. The second condition is regarding the stability of the running conditions.

III. CONCLUSIONS

1. Magnetic cooling devices offer a similar or improved performance than conventional vapor compression refrigeration systems.
2. Performance is found to be best at Curie temperature which is around 20 °C. Thus, it is best suited for comfort air conditioning applications.
3. Magnetic refrigeration is a compelling technique in the areas where extra cost is not a constraint such as in military applications, off shore drilling platforms.
4. The use of hybrid technology involving both magnetic cooling and vapor compression can complement each other creating a more efficient system.
5. Super conducting magnets are feasible only for large scale application.

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