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A review on: Magnetic Refrigeration – Emerging Technology in the field of Refrigeration

Prof. Vatsal S. Patel[1] Prof. Jay D. Patel[2] Prof. Bharat K.Khalasi[3]
[1,2,3]Department of Mechanical Engineering
[1,2,3]Pacific School of Engineering, Surat, Gujarat.

Abstract— The objective of this effort is to study the Magnetic Refrigeration which uses solid materials as the refrigerant. These materials demonstrate the unique property known as magneto caloric effect, which means that they increase and decrease in temperature when magnetized /demagnetized. This effect has been observed for many years and was used for cooling near absolute zero. This system uses a magnetic solid material as a refrigerant. Magneto caloric effect is the basis of the magnetic refrigeration. This technology is environmental friendly.

Key words: Magnetic Refrigeration, magnetized /demagnetized

I. INTRODUCTION

Refrigeration consumes the large part of energy supply of the world. There are different types of cycles used to obtain the required temperatures. One of them is most efficient, mature and reliable cycle is vapour compression cycle. Vapor-compression refrigeration is one of the many refrigeration cycles available for use. It has been and is the most widely used method for air-conditioning of large public buildings, offices, private residences, hotels, hospitals, theatres, restaurants and automobiles. But, Vapour compression cycle uses hazardous chemicals as refrigerant like CFC'S. This cycle is reached to its highest energy limit. The performance of this cycle cannot be increased. This system requires a compressor, which requires large amount of mechanical power and also vibrations, noise are carried along with it. The COP of this cycle is 40% of Carnot COP. The refrigerant contributes to environmental problems like ozone layer depletion and global warming.

Magnetic refrigeration is a cooling technology based on the magneto caloric effect. This technique can be used to attain extremely low temperatures (well below 1 Kelvin), 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 (1880) and the fundamental principle was suggested by Debye (1926) and Giauque (1927). The first working magnetic refrigerators were constructed by several groups beginning in 1933. Magnetic refrigeration was the first method developed for cooling below about 0.3 K (a temperature attainable by 3He refrigeration, that is pumping on the 3He vapors) [1].

B.F. Yu et al [3] gives the concept of magneto caloric effect is explained. The development of the magnetic material, magnetic refrigeration cycles, magnetic field and the regenerator of room temperature magnetic refrigeration is introduced. Finally some typical room temperature magnetic refrigeration prototypes are reviewed.

Engin GED K et al [7] studied about a new refrigeration technology interested and Magnetic Refrigeration based on the magneto-caloric effect (MCE) has become a promising competitive technology for the conventional gas compression/ expansion technique contributed climate change occurred negative environmental effect due to increasing energy consumption is investigated. Magnetic Refrigeration is a refrigeration type based on magneto caloric effect (MCE). It is possible to make refrigeration under 1K temperatures with the magnetic refrigeration and liquefaction of hydrogen and helium. Recently, there have been two breakthroughs in magnetic-refrigeration researches: one is that the magnetic refrigerators on near room temperature,; the other one is that to discover a new magnetic materials for room temperature applications. The new materials are manganese–iron–phosphorus and arsenic (MnFe(P,As)) alloys. Nowadays rotary and reciprocating type magnetic refrigerators are exist and studies is going on for the developments of this refrigerators.

II. PRINCIPLE OF MAGNETIC REFRIGERATION

- Magneto calorific effect (MCE) is the basic principle on which the cooling is achieved.
- All magnets bear a property called Currie effect i.e. If a temperature of magnet is increased from lower to higher range at certain temperature magnet looses the magnetic field.
- Curie temperature: Depends on individual property of each material. Phase transition temperature .MCE is the largest around the Curie temperature of the material.
- As Energy input to the magnet is increased the orientation of the magnetic dipoles in a magnet starts loosing orientation. And vice a versa at Curie temperature as magnet looses energy to the media it regains the property

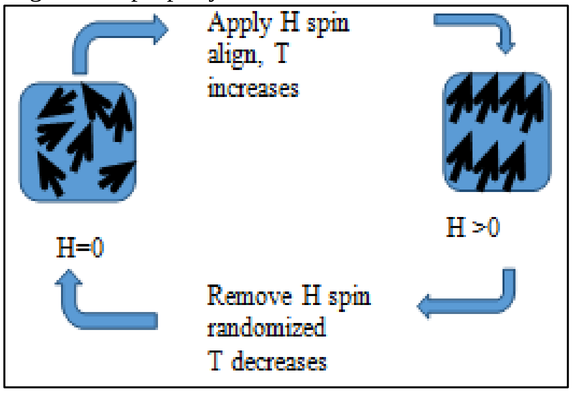

Fig. 1: Effect of magnetic field on enthalpy

As shown in the figure - 3, when the magnetic material is placed in the magnetic field, the thermometer attached to it shows a high temperature as the temperature of it increases. But on the other side when the magnetic material is removed from the magnetic field, the thermometer shows low temperature as its temperature decreases.[2]

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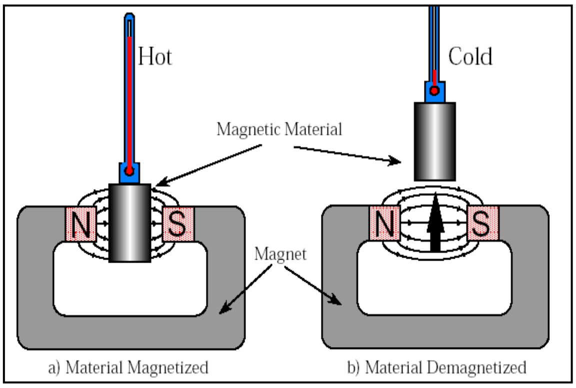

Fig. 2: Effect of magnetic field on temperature

A. Working of Magnetic Refrigeration [Mr] Cycle

The magnetic refrigeration is mainly based on magneto caloric effect according to which some materials change in temperature when they are magnetized and demagnetized. Near the phase transition of the magnetic materials, the adiabatic application of a magnetic field reduces the magnetic entropy by ordering the magnetic moments. This results in a temperature increase of the magnetic material. This phenomenon is practically reversible for some magnetic materials; thus, adiabatic removal of the field revert the magnetic entropy to its original state and cools the material accordingly. This reversibility combined with the ability to create devices with inherent work recovery, makes magnetic refrigeration a potentially more efficient process than gas compression and expansion. The efficiency of magnetic refrigeration can be as much as 50% greater than for conventional refrigerators.

The AMR refrigeration cycle consists of four steps:

1) Magnetization, which increases the temperature of the regenerator with a subsequent heat transfer to the fluid,
2) the cold blow where hot fluid is displaced from the regenerator and into the HHEX where the fluid rejects heat to the surroundings,
3) demagnetization, which decreases the temperature of the regenerator which results in heat absorption from the fluid and
4) the hot blow which displace cold fluid from regenerator towards the CHEX where the fluid absorbs heat from the cooling load.
5) Co-efficient of Performance:

COP= Qc / Win

Qc is the cooling power i.e. the heat absorbed from the cold end. Win is the work input into magnetic refrigerator.

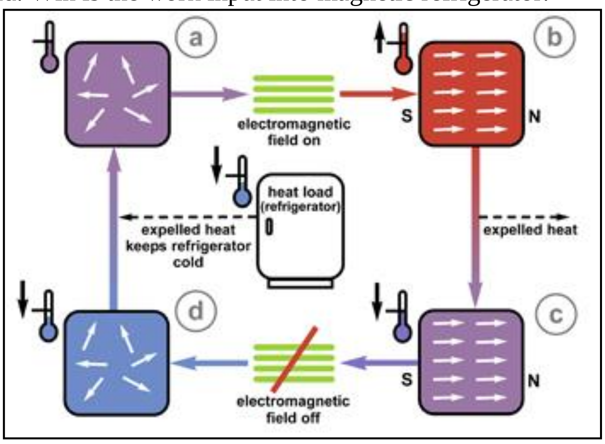

Fig. 3: Working of magnetic refrigeration

B. Processes

1) Adiabatic Magnetization

The substance is placed in an insulated environment. The increasing external magnetic field (+H) causes the magnetic dipoles of the atoms to align, thereby decreasing the material's magnetic entropy and heat capacity. Since overall energy is not lost (yet) and therefore total entropy is not reduced (according to thermodynamic laws), the net result is that the item heats up (T + ΔTad).

C. Isomagnetics Enthalpic Transfer

This added heat can then be removed by a fluid like water or helium for example (-Q). The magnetic field is held constant to prevent the dipoles from reabsorbing the heat. Once sufficiently cooled, the magneto caloric material and the coolant are separated (H=0).

D. Adiabatic Demagnetization

The substance is returned to another adiabatic (insulated) condition so the total entropy remains constant. However, this time the magnetic field is decreased, the thermal energy causes the domains 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).

E. 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). Once the refrigerant and refrigerated environment is in thermal equilibrium, the cycle begins a new one. [1]

III. COMPARISON

The magneto caloric effect can be utilized in a thermodynamic cycle to produce refrigeration.

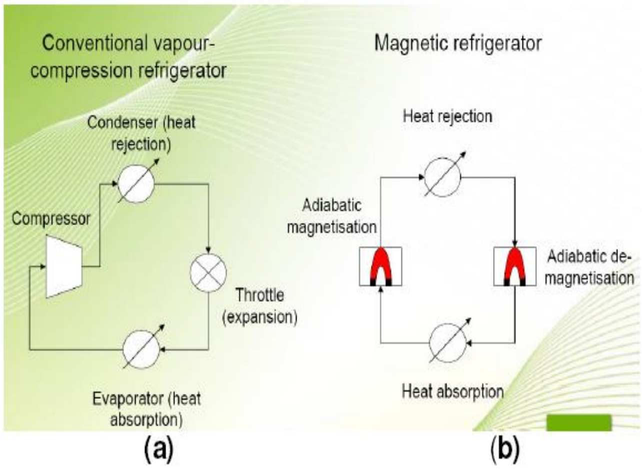

Fig. 4: Comparison between VCR and MR [7]

Disadvantages of vapor compression and vapor absorption refrigeration:

1) Produces toxic gases and chloro-fluoro carbon, thus reducing ozone layer depletion.
2) Very low temperature cannot be achieved.
3) The unit produces noise and vibration compared to magnetic refrigerators.

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4) Compressor is needed to produce required pressure.
5) An unnecessarily large motor is required to overcome the inertia of the stationary compressor in case of heavy load applications.
6) Large torque loads are placed on the motor, compressor mounts, bearings and belts at start up.
7) In the lithium bromide absorption refrigeration system, lithium bromide is corrosive in nature and in case of the ammonia system, ammonia is toxic, flammable.

A. *Merits of Magnetic Refrigeration*

1) *Technical*

- High efficiency:-As the magneto caloric effect is highly reversible, the thermo dynamic efficiency of the magnetic refrigerator is high. It is somewhat 50% more than Vapor Compression cycle.
- Reduced operating cost:-As it eliminates the most inefficient part of today's refrigerator i.e. comp. The cost reduces as a result.
- 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.
- Reliability:-Due to the absence of gas, it reduces concerns related to the emission into the atmosphere and hence is reliable one.

2) *Socio-Economic*

- Competition in global market:-Research in this field will provide the opportunity so that new industries can be set up which may be capable of competing the global or international market.
- Low capital cost:-The technique will reduce the cost as the most inefficient part comp. is not there and hence the initial low capital cost of the equipment.
- Key factor to new technologies:-If the training and hardware's are developed in this field they will be the key factor for new emerging technologies in this world. [2]

3) *Demerits*

- Large MCE of magnetic material is required
  - Narrow temperature region
  - Impurities & structural imperfections
- Strong magnetic field is required
  - Superconductors – very expensive
  - Electromagnets – needs greater electric power
  - Permanent magnets – Max. field strength of 1.5T

IV. REQUIREMENTS FOR PRACTICAL APPLICATIONS

A. *Magnetic Materials*

Only a limited number of magnetic materials possess a large enough magneto caloric effect to be used in practical refrigeration systems. The search for the "best" materials is focused on rare earth metals, either in pure form or combined with other metals into alloys and compounds. The magneto caloric effect is an intrinsic property of a magnetic solid. This thermal response of a solid to the application or removal of magnetic fields is maximized when the solid is near its magnetic ordering temperature. The magnitudes of the magnetic entropy and the adiabatic temperature changes are strongly dependent upon the magnetic order process: the magnitude is generally small in antiferromagnets, ferrimagnets and spin glass systems.

Currently, alloys of gadolinium producing 3 to 4 K per tesla of change in a magnetic field can be used for magnetic refrigeration or power generation purposes. Recent research on materials that exhibit a giant entropy change showed that Gd5(SixGe1 − x)4, La(FexSi1 − x)13Hx and MnFeP1 − xAsx alloys, for example, are some of the most promising substitutes for Gadolinium and its alloys (GdDy, GdTy, etc...). These materials are called giant magneto caloric effect materials (GMCE).

Gadolinium and its alloys are the best material available today for magnetic refrigeration near room temperature since they undergo second-order phase transitions which have no magnetic or thermal hysteresis involved. [3]

- Properties of Gadolinium:
  - Rare-earth metal

Fig. 5:

  - Belongs to the group of lanthanides
  - Curie temperature of 294 K
  - 7 unpaired electrons in an intermediate shell; thus strong magnetic moment

Increase in Magneto-caloric Effect of Gadolinium as Magnetic Field increases by 1 Tesla[6]

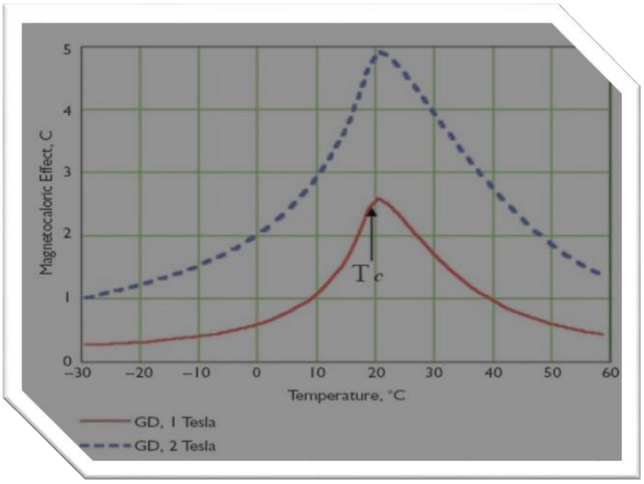

Fig. 5: Gadolinium as refrigerant

B. *Regenerators*

Magnetic refrigeration requires excellent heat transfer to and from the solid magnetic material. Efficient heat transfer requires the large surface areas offered by porous materials. When these porous solids are used in refrigerators, they are referred to as "regenerators".

Typical regenerator geometries include:

a) Tubes

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b) Perforated plates
c) Wire screens
d) Particle beds

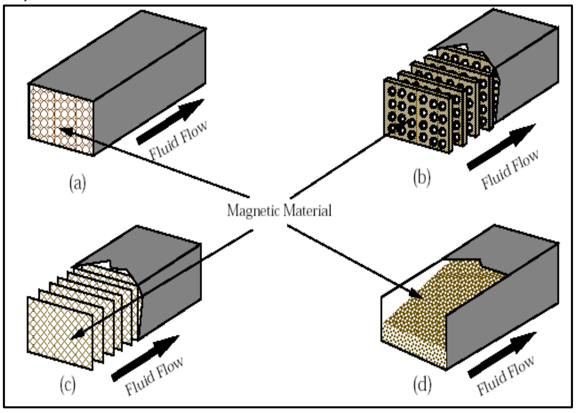

Fig. 6: Types of regenerators

C. *Super Conducting Magnets*

Most practical magnetic refrigerators are based on superconducting magnets operating at cryogenic temperatures (i.e., at -269 C or 4 K).These devices are electromagnets that conduct electricity with essentially no resistive losses. The superconducting wire most commonly used is made of a Niobium-Titanium alloy. Only superconducting magnets can provide sufficiently strong magnetic fields for most refrigeration applications. A typical field strength is 8 Tesla (approximately 150,000 times the Earth's magnetic field).An 8 Tesla field can produce a magneto caloric temperature change of up to 15 C in some rare-earth materials.

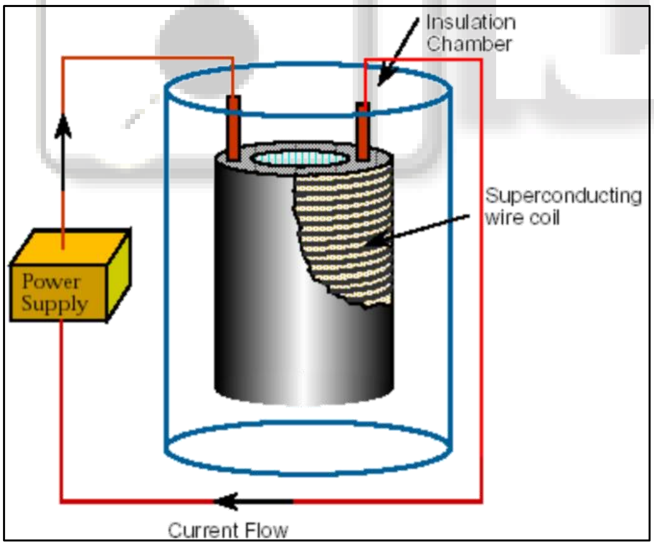

Fig. 7: Super conducting magnets

D. *Active Magnetic Regenerators (Amr)*

A regenerator that undergoes cyclic heat transfer operations and the magneto caloric effect is called an Active Magnetic Regenerator (AMR).An AMR should be designed to possess the following attributes:
These requirements are often contradictory, making AMR's difficult to design and fabricate.

1) High heat transfer rate
2) Low pressure drop of the heat transfer fluid
3) High magneto caloric effect
4) Sufficient structural integrity
5) Low thermal conduction in the direction of fluid flow
6) Low porosity
7) Affordable materials
8) Ease of manufacture

1) *Types of AMR*

There are two main AMR designs: the reciprocating AMR and the rotating AMR, as shown on Fig. The difference between the two designs is that the rotating AMR consists of a wheel with multiple regenerators that rotates such that one regenerator enters the magnetic field and rejects heat while another regenerator is removed from the magnetic field and absorbs heat.

This design allows the rotating AMR to continuously produce cooling. Compared to this configuration, the reciprocating AMR typically only has a single regenerator and perform each step of the AMR cycle sequentially and thus only produces cooling during the cold blow. During the cyclical steady-state, there is a nearly linear temperature profile through the regenerator going from TC at the CHEX to TH at the HHEX [7].

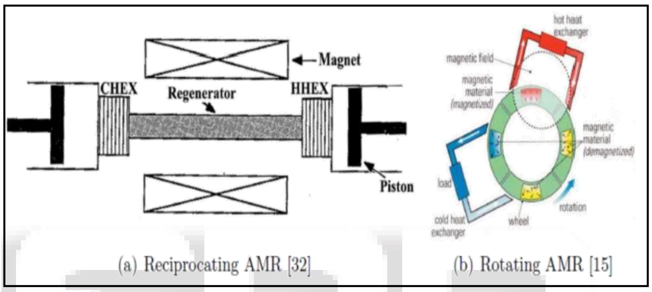

Fig. 8:

V. APPLICATIONS

A. *A Rotary AMR Liquefier*

The Cryofuel Systems Group is developing an AMR refrigerator 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.

B. *Further 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. An option to realize magnetic freezing applications could be the use of superconducting magnets. However, this may only be economic in the case of rather large refrigeration units. Such are used for freezing, e.g. in cooling plants in the food industry or in large marine freezing applications.[5]

Some of the 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

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VI. CONCLUSION

Magnetic refrigeration is a technology that has proven to be environmentally safe. Computer models have shown 25% efficiency improvement over vapor compression systems. In order to make the Magnetic Refrigerator commercially viable, scientists need to know how to achieve larger temperature swings. Two advantages to using Magnetic Refrigeration over vapor compressed systems are no hazardous chemicals used and they can be up to 60% efficient.

Magnetic refrigeration is undoubtedly a promising technology that should be encouraged because of its numerous advantages, in particular energy saving and environmental benefits. In a near future magnetic refrigerators may come to cool our home.

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