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1.0 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. Recently materials are being developed which have sufficient temperature and entropy change to make them useful for a wide range temperature applications. Benefits of magnetic refrigeration are lower cost, longer life, lower weight and higher efficiency because it only requires one moving part-the rotating disc on which the magneto caloric material is mounted. The unit uses no gas compressor, no pumps, no working fluid, no valves and no ozone destroying chlorofluorocarbons/hydro chlorofluorocarbons. potential commercial applications include cooling of electronics, super conducting components used in telecommunications equipment, home and commercial refrigerator ,heat pumps, air conditioning for homes, offices and automobiles and virtually any places where refrigeration is needed.

2.0 INTRODUCTION

Magnetic refrigeration is a cooling technology based on the magnetocaloric 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.

2.1 HISTORY

The effect was discovered in pure iron in 1881 by E. Warburg. Originally, the cooling effect varied between 0.5 to 2 K/T.

Major advances first appeared in the late 1920s when cooling via adiabatic demagnetization was independently proposed by two scientists: Debye (1926) and Giauque (1927).

The process was demonstrated a few years later when Giauque and MacDougall in 1933 used it to reach a temperature of 0.25 K. Between 1933 and 1997, a number of advances in utilization of the MCE for cooling occurred.

This cooling technology was first demonstrated experimentally by chemist Nobel Laureate William F. Giauque and his colleague Dr. D.P. MacDougall in 1933 for cryogenic purposes (they reached 0.25 K)

Between 1933 and 1997, a number of advances occurred which have been described in some reviews.

In 1997, the first near room temperature proof of concept magnetic refrigerator was demonstrated by Prof. Karl A. Gschneidner, Jr. by the Iowa State University at Ames Laboratory. This event attracted interest from scientists and companies worldwide that started developing new kinds of room temperature materials and magnetic refrigerator designs.

Refrigerators based on the magnetocaloric effect have been demonstrated in laboratories, using magnetic fields starting at 0.6 T up to 10 teslas. Magnetic fields above 2 T are difficult to produce with permanent magnets and are produced by a superconducting magnet (1 tesla is about 20,000 times the Earth's magnetic field).

2.2 MAGNETO CALORIC EFFECT

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 low temperature physicists, due to the application of the process specifically to affect a 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 (magnetocaloric) material to become disoriented from the magnetic field by the agitating action of the thermal energy (phonons) present in the material. If the material is isolated so that no energy is allowed to (e) migrate into the material during this time (i.e. an adiabatic process), the temperature drops as the domains absorb the thermal energy to perform their reorientation. The randomization of the domains occurs in a similar fashion to the randomization at the curie temperature, except that magnetic dipoles overcome a decreasing external magnetic field while energy remains constant, instead of magnetic domains being disrupted from internal ferromagnetism as energy is added.

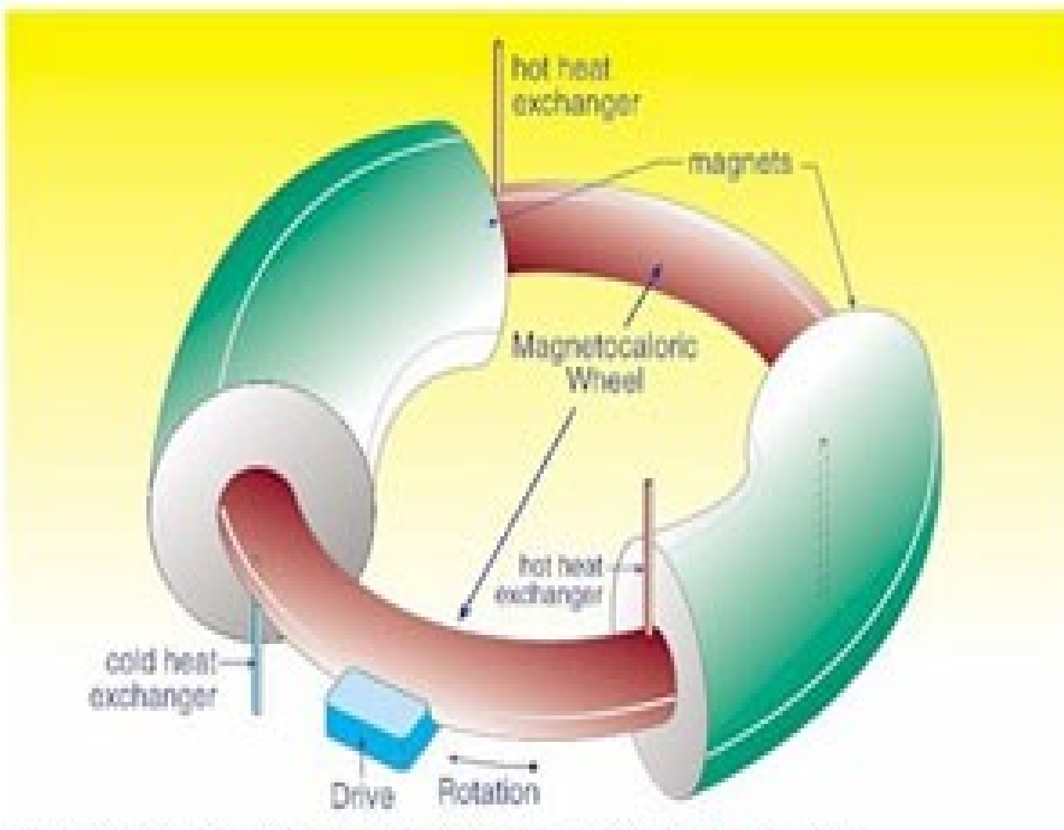
One of the most notable examples of the magnetocaloric effect is in the chemical element gadolinium and some of its alloys. Gadolinium's temperature is observed to increase when it enters certain magnetic fields. When it leaves the magnetic field, the temperature returns to normal. The effect is considerably stronger for the gadolinium alloy $Gd_5(Si_2Ge_2)$. Praseodymium alloyed with nickel ($PrNi_5$) has such a strong magnetocaloric 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.**

3.0 CONSTRUCTION AND WORKING

3.1 COMPONENTS REQUIRED

1. Magnets
2. Hot Heat exchanger
3. Cold Heat Exchanger
4. Drive
5. Magneto caloric wheel



An artist's rendition of a rotary magnetic refrigerator.

Figure 1

Magnets: - Magnets are the main functioning element of the magnetic refrigeration. Magnets provide the magnetic field to the material so that they can loose or gain the heat to the surrounding and from the space to be cooled respectively.

Hot Heat Exchanger: - The hot heat exchanger absorbs the heat from the material used and gives off to the surrounding. It makes the transfer of heat much effective.

Cold Heat Exchanger:-The cold heat exchanger absorbs the heat from the space to be cooled and gives it to the magnetic material. It helps to make the absorption of heat effective.

Drive: - Drive provides the right rotation to the heat to rightly handle it. Due to this heat flows in the right desired direction.

Magneto caloric Wheel: - It forms the structure of the whole device. It joins both the two magnets to work properly.

3.2 WORKING PRINCIPLE

As shown in the figure 2, 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.

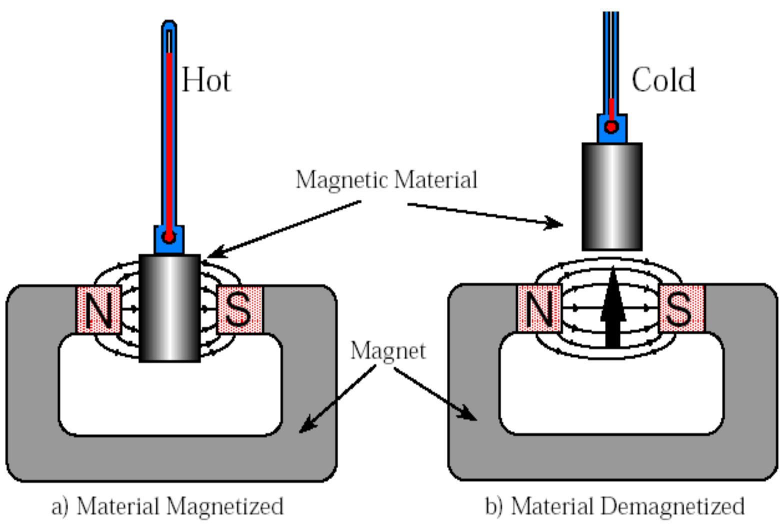


Figure 2

3.3 WORKING

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.

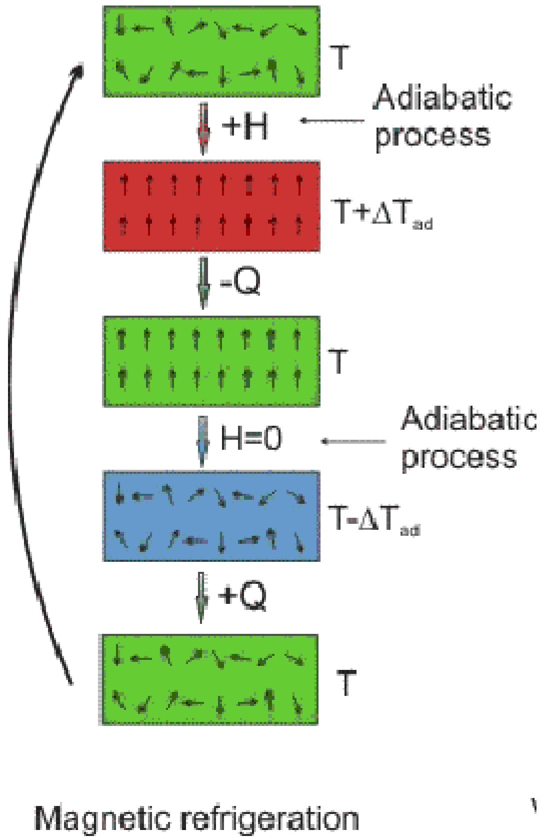


Figure 3

The process is performed as a refrigeration cycle, analogous to the Carnot cycle, and can be described at a starting point whereby the chosen working substance is introduced into a magnetic field (i.e. the magnetic flux density is increased). The working material is the refrigerant, and starts in thermal equilibrium with the refrigerated environment.

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 ($T + \Delta T_{ad}$).

Isomagnetic 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 magnetocaloric material and the coolant are separated (H=0).

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).

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.

3.4 PROPER FUNCTIONING

The place we want to cool it, we will apply magnetic field to the material in that place and as its temperature increases, it will absorb heat from that place and by taking the magnetic material outside in the surroundings, we will remove the magnetic material from magnetic field and thus it will loose heat as its temperature decreases and hence the cycle repeats over and again to provide the cooling effect at the desired place.

4.0 REQUIREMENTS FOR PRATICAL APPLICATIONS

4.1 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.

Magnetic Refrigeration

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 $Gd_5(Si_xGe_{1-x})_4$, $La(Fe_xSi_{1-x})_{13}H_x$ and $MnFeP_{1-x}As_x$ 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.

4.2 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

(b) Perforated plates

(c) Wire screens

(d) Particle beds

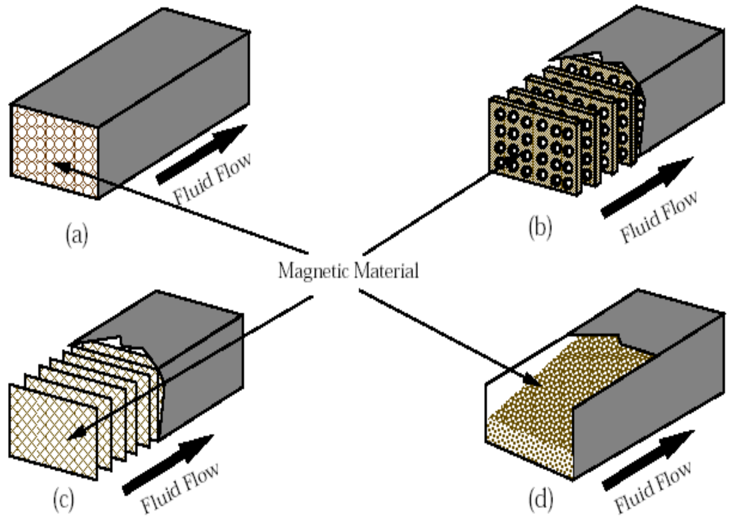


Figure 4

4.3 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.

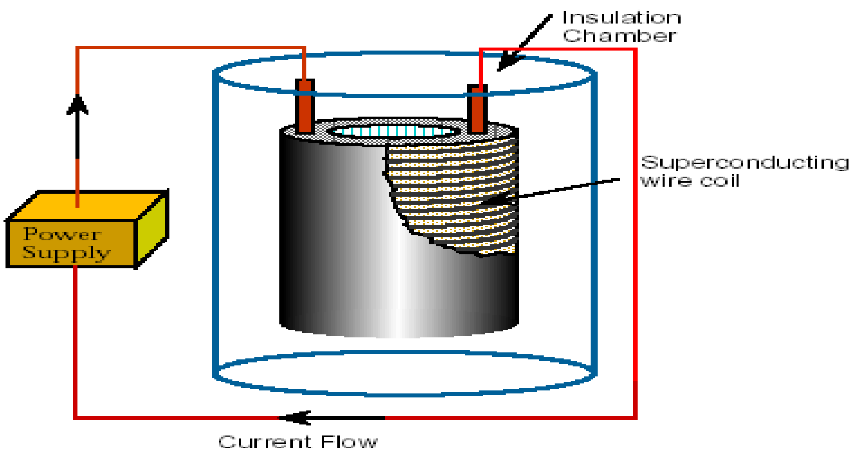


Figure 5

4.4 Active Magnetic Regenerators (AMR's)

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

5.0 APPLICATIONS

5.1 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.

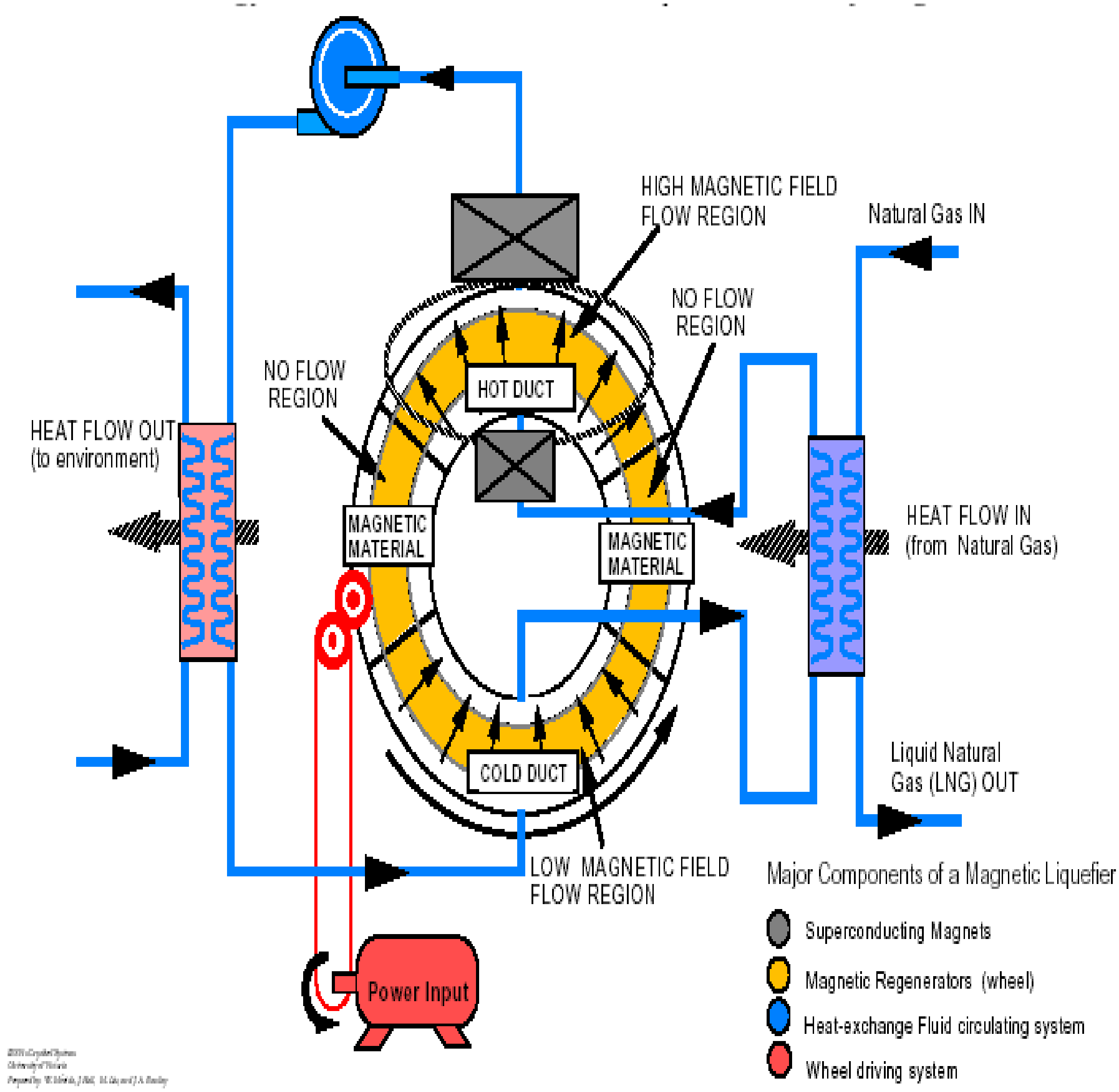


Figure 6

5.2 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.

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

Some of the future applications are

Magnetic Refrigeration

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

6.0 COMPARISON

6.1 Comparison between magnetic refrigeration and conventional refrigeration

The magneto caloric effect can be utilized in a thermodynamic cycle to produce refrigeration. Such a cycle is analogous to conventional gas-compression refrigeration

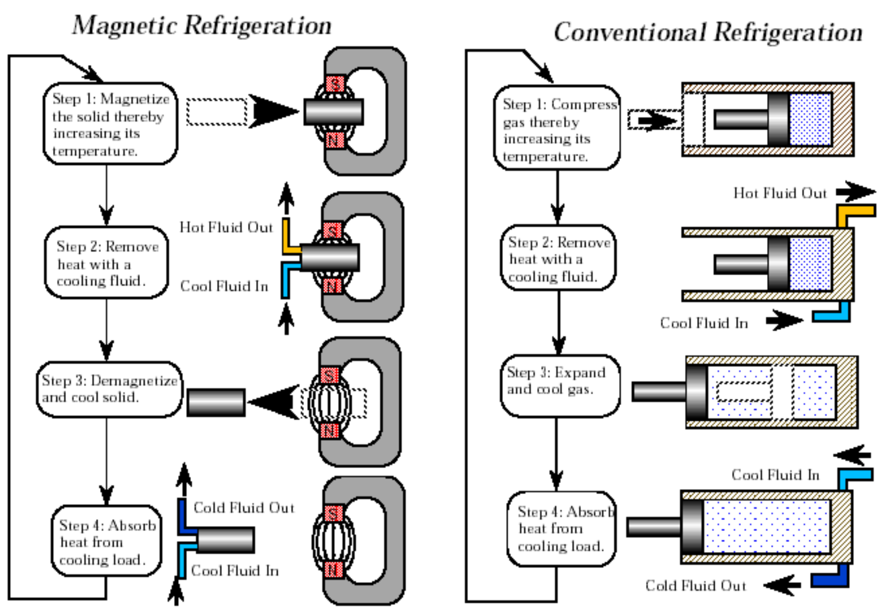


Figure 7

6.1 Co-efficient of Performance:

Co-efficient of Performance of magnetic refrigeration is given by the equation

$$COP= Q_c/W_{in}$$

Q_c is the cooling power i.e. the heat absorbed from the cold end.

W_{in} is the work input into magnetic refrigerator.

7.0 BENEFITS

7.1 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.

7.2 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 hard wares are developed in this field they will be the key factor for new emerging technologies in this world.

7.3 ADVANTAGES OVER VAPOUR COMPRESSION AND VAPOR ABSORPTION CYCLE CYCLES

Magnetic refrigeration performs essentially the same task as traditional compression-cycle gas refrigeration technology. Heat and cold are not different qualities; cold is merely the relative absence of heat. In both technologies, cooling is the subtraction of heat from one place (the interior of a home refrigerator is one commonplace example) and the dumping of that heat another place (a home refrigerator releases its heat into the surrounding air). As more and more heat is subtracted from this target, cooling occurs. Traditional refrigeration systems - whether air-conditioning, freezers or other forms - use gases that are alternately expanded and compressed to perform the transfer of heat. Magnetic refrigeration systems do the same job, but with metallic compounds, not gases. Compounds of the element ***gadolinium*** are most commonly used in magnetic refrigeration, although other compounds can also be used.

Magnetic refrigeration is seen as an environmentally friendly alternative to conventional vapor-cycle refrigeration. And as it eliminates the need for the most inefficient part of today's refrigerators, the compressor, it should save costs. New materials described in this issue may bring practical magneto caloric cooling a step closer. A large magnetic entropy change has been found to occur in $MnFeP_{0.45}As_{0.55}$ at room temperature, making it an attractive candidate for commercial applications in magnetic refrigeration.

The added advantages of MR over Gas Compression Refrigerator are compactness, and higher reliability due to Solid working materials instead of a gas, and fewer and much slower moving parts our work in this field is geared toward the development of magnetic alloys with MCEs, and phase transitions temperatures suitable for hydrogen liquefaction from Room temperature down to 20 K.

7.4 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 of order 001K cannot be achieved.
3. The unit produces noise and vibration compared to magnetic refrigerators.
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.

8. CASE STUDY

T. Utaki, T. Nakagawa T. A. Yamamoto and T. Numazawa from Graduate school of Engineering, Osaka University Osaka, 565-0871, Japan and K. Kamiya from National Institute for Materials Science, Tsukuba Magnet Laboratory ,Tsukuba, Ibaraki, 305-0003, Japan have constructed a Active Magnetic Regenerative(AMR) cycle for liquefaction of hydrogen.

The magnetic refrigerator model they have constructed is based on a multistage active magnetic regenerative (AMR) cycle. In their model, an ideal magnetic material with constant magneto caloric effect is employed as the magnetic working substance. The maximum applied magnetic field is 5T, and the liquid hydrogen production rate is 0.01t/day. Starting from liquid nitrogen temperature (77K), it is assumed that four separate four stages of refrigeration are needed to cool the hydrogen. The results of the simulation show that the use of a magnetic refrigerator for hydrogen liquefaction is possibly more than the use of conventional liquefaction methods.

In general, they have found that, it is helpful to precool hydrogen prior to liquefaction using a cryogenic liquid such as Liquid nitrogen (LN) or liquid natural gas (LNG).Therefore, we chose three system configurations to analyze with our numerical simulation. In the first case, the supplied hydrogen is precooled by the AMRR only. In this case it is assumed that the magnetic refrigeration system precools the hydrogen from 300 K to 22 K using approximately 7-9 stages of AMRR. In the second case, the supplied hydrogen is precooled from 300 K to 77 K by LN and from 77 K to 22 K by 3 stages of AMRR. In the third case, the supplied hydrogen is precooled from 300 K to120 K by LNG and from 120 K to 22 K by 5 stages of AMRR.

The best performance was achieved by a combined CMR plus a 3-stage AMRR with LN precooling. It had a total work input of 3.52 kW and had a liquefaction efficiency of 46.9 %. This provides promise that magnetic refrigeration systems may be able to achieve higher efficiency than conventional liquefaction methods.

9.0 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.

There are still some thermal and magnetic hysteresis problems to be solved for these first-order phase transition materials that exhibit the GMCE to become really useful; this is a subject of current research. This effect is currently being explored to produce better refrigeration techniques, especially for use in spacecraft. This technique is already used to achieve cryogenic temperatures in the laboratory setting (below 10K).

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