A Study of Magnetic Refrigeration

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ABSTACT

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, novalves 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.

CHAPTER 1 INTRODUCTION

1.1 Overview

Refrigeration is the process of removing heat from matter which may be a solid, a liquid, or a gas. Removing heat from the matter cools it, or lowers its temperature. In the mechanical refrigeration a refrigerant is a substance capable of transferring heat that it absorbs at low temperatures and pressures. By means of expansion, compression and cooling medium such asair or water, the refrigerant removes heat from a substances and transfers it to a cooling medium.

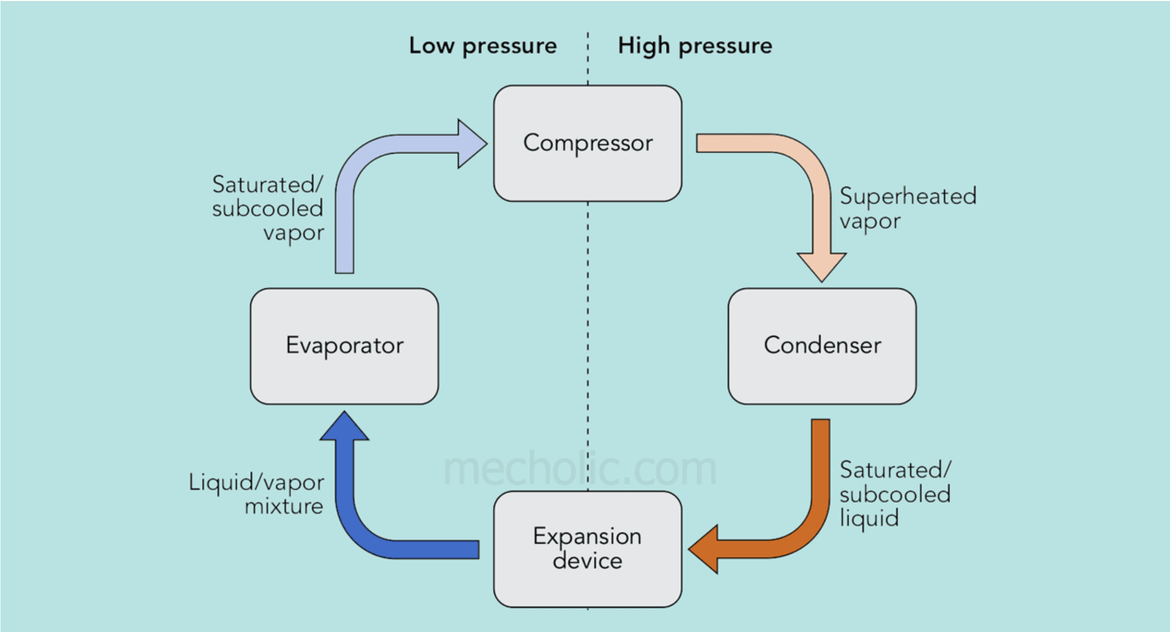

Fig.1: Basic refrigeration cycle

Our society is highly dependent on reliable cooling technology. Refrigeration is critical to ourhealth and global economy. The consumer application includes air conditioning, food preservation, air dehumidification, beverage dispensing and ice making without refrigeration the food supply would still be seasonal and limited to locally produce nonperishable items. Modern refrigeration is almost entirely based on a compression/ expansion refrigeration cycle. It is mature, reliable and relatively low cost technology. Over the years, all parts of a conventional refrigerator were considerably improved due to extended research and development efforts. Furthermore, some liquids used as refrigerants are hazardous chemicals, while other eventually escape into the environment contributing towards ozone layer depletion and global warming and therefore, conventional refrigeration ultimately promotes deleterious trends in the global climate.

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.

Magnetic refrigeration of adiabatic demagnetization is a cooling technology based on magneto caloric effect, an intrinsic property of magnetic solids. The refrigerant is often a paramagnetic salt, such as cerium magnesium nitrate. The active magnetic dipoles in this case are those of the electron shells of paramagnetic atoms. A strong magnetic field is applied to the refrigerant, forcing its various magnetic dipoles to align and putting these degrees of freedom of the refrigerant into the state of lowered entropy. The heat sink then absorbs the heat released by the refrigerant due to its loss of entropy. Thermal contact with the heat sink is then broken so that the system is insulated, and magnetic field is switched off. This increases the heat capacity of the refrigerant, thus decreasing its temperature below the temperature of heat sink. Becausefew materials exhibit the needed properties at room temperature, applications have so far beenlimited to cryogenics and research.

1.2 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 usedit 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 starteddeveloping new kinds of room temperature materials and magnetic refrigerator designs.

Refrigerators based on the magneto-caloric effect have been demonstrated in laboratories, using magnetic fields starting at 0.6 T up to 10 tesla. 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).

1.3 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 (magneto-caloric) 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 migrate into the material during this time (i.e. an adiabatic process), the temperature drops as the domains absorb the thermal energy to performtheir 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.

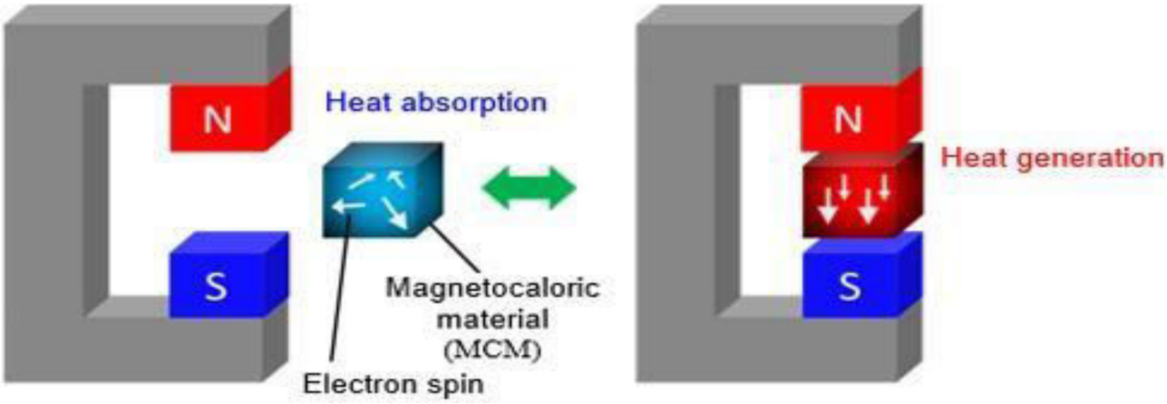

Fig.2: Magneto-caloric effect

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 returns to normal. The effect is considerably stronger for the gadolinium alloy Gd5 (Si2Ge2). Praseodymium alloyed with nickel (Pr –Ni 5) 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.

CHAPTER 2 LITRATURE REVIEW

- **T. Utaki, et al.,** This paper focuses on magnetic refrigerator model which theyconstructed is based on a multistage active magnetic regenerative (AMR) cycle. In theircurrent model, an ideal magnetic material with constant magneto caloric effect is employed as the magnetic working substance. The maximum applied field is 5 T, and the liquid hydrogen production rate is 0.01 t/day. Starting from liquid nitrogen temperature (77 K), it is assumed that four separate 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 efficient than the use of conventional liquefaction methods. There are several candidate arrangements of magnetic refrigeration liquefaction cycles starting from either room temperature (300 K), or from the temperature of liquid natural gas (120 K).They studied a variety of magnetic refrigeration system configurations for hydrogen liquefaction and evaluated their system parameters and work input by numerical simulation. The best performancewas achieved by a combined CMR plus a 3-stage AMR with LN 2 precooling. It had a total work input of 3.52 kW and had a liquefaction efficiency of 46.9 %. This providespromise that magnetic refrigeration systems may be able to achieve higher efficiency than conventional liquefaction methods.
- **Smt. Kinnari S. Damania,** This paper focuses on the working principle, comparison with conventional methods, different magneto caloric materials, benefits and practical applications of magnetic refrigeration. 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 cooling of electronics, superconducting components used in telecommunication equipment, home and commercial refrigerator, air conditioning for homes, offices and automobiles and virtually any places where refrigeration is needed. Large MCE of magnetic material is investigated for room temperature magnetic cooling application strong magnetic field is required. It is environmentally protective technology.

- **Yash Kulkarni,** 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 forcooling 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 basedheat 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. Magnetic materials available for room Temperature magnetic refrigeration are mainly Gd, Gdsige alloys, mn as-like materials,perovskite like Materials. The simplicity of the design of the refrigeration operation makes it even more desirable.
- **Dr. L. C. Singal, et al,** Magnetic cooling is an old concept but being tried for day todayapplications in order to overcome the disadvantages of conventionally used vapour compression refrigeration systems regarding reduced power input and freedom from Ozone Depletion and Global Warming. Long back, it has been successfully applied in the cryogenic temperature ranges. Magnetic refrigeration is based on the magneto- caloric effect, a characteristic present in all magnetic materials and their alloys. Magnet caloric effect means that the temperature of a suitable material changes when magnetized or de-magnetized. Magnetization of a magneto-caloric material is equivalent to the compression of a gas (heating), while demagnetization is equivalent to expansion of a gas (cooling). The first most requirements are that these variations must be achievable speedily, repeatedly, reversibly with minimum energy losses. In this paper, the applicability of this method for room temperature refrigeration and air conditioning has been studied. Firstly, the magnetic refrigeration and vapour compression systems have been compared.

Secondly, the magneto – caloric materials and their requirements has been listed. Thirdly, the effect of various parameters as strength of the magnetic field, regenerator configuration, temperature span and refrigerant fluid on the performance of magnetic refrigeration has been discussed. Lastly and not the least, the advantages and disadvantages has been mentioned. Magnetic refrigeration seems to posses' great potential for future generations. Performance has been found to be best at Curie temperature which is around 200C. Thus it can be best suited for comfort air conditioning applications. Presently there are number of contradictions in improving the performance of magnetic refrigeration. But the day these are overcome, it will be a boon for the coming generations because of the inherent advantages the magnetic refrigeration possess over the conventional vapour compression refrigeration systems. (x) Use of hybrid technologies employing both magnetic cooling and vapour compression could complement each other, creating a more efficient and powerful device for those cases where the extra cost would be assumable, as in military applications and off-shore drilling platforms

- **K. Engelbrechta, et al,** Active magnetic regenerator AMR refrigerators represent an alternative to vapour compression technology that relies on the magneto-caloric effectin a solid refrigerant. Magneto-caloric materials are in development and properties are reported regularly. Recently, there has been an emphasis on developing materials with a high entropy change with magnetization while placing lower emphasis on the adiabatic temperature change. This work uses model magneto-caloric materials and a numerical AMR model to predict how the temperature change and entropy change with magnetization interact and how they affect the performance of a practical system. The distribution of the magneto-caloric effect as a function of temperature was also studied. It was found that the adiabatic temperature change in a magneto-caloric material can be more important than the isothermal entropy change for certain conditions. A material that exhibits a sharp peak in isothermal entropy change was shown to produce a significantly lower cooling power than a material with a wide peak in a practical AMR system. Finally, it was shown that materials with pronounced spikes in show reduced performance com with constant and equal RCAP. This could make materials that exhibit a large peak in over a narrow temperature band less desirable for AMR applications, especially for a single material regenerator. MCM research should emphasize developing materials with high over a broad temperature range rather than solely increasing peak values of two materials.

CHAPTER 3 METHODOLOGY

3.1CONSTRUCTION AND WORKINGCOMPONENTS REQUIRED: -

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.
2. **Hot Heat Exchanger: -** The hot heat exchanger absorbs the heat from the material usedand gives off to the surrounding. It makes the transfer of heat much effective.
3. **Cold Heat Exchanger: -**The cold heat exchanger absorbs the heat from the space to becooled and gives it to the magnetic material. It helps to make the absorption of heat 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 the structure of the whole device. It joins both the two magnets to work properly.

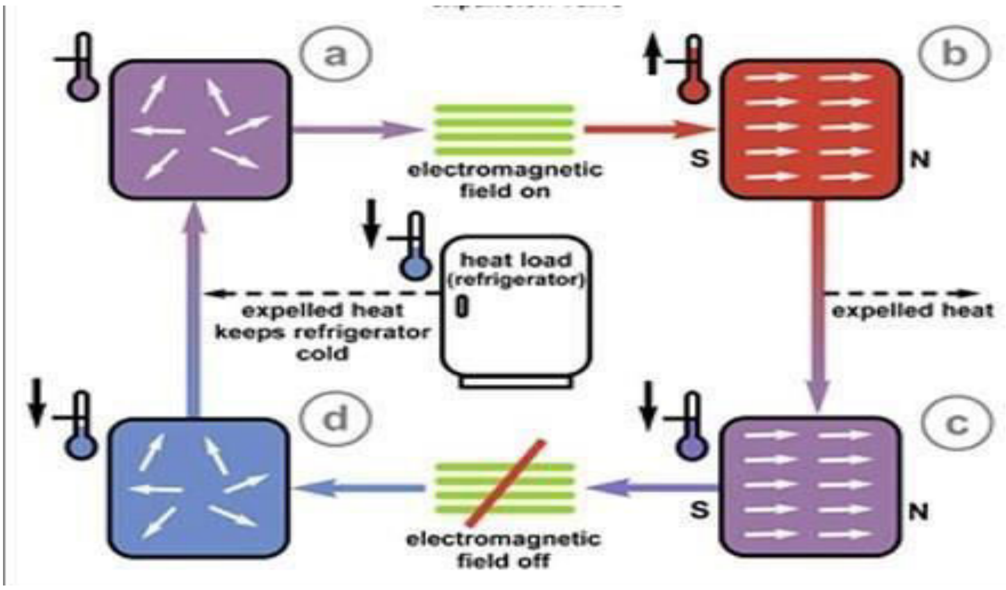

Fig.3: Construction of Magnetic Refrigeration

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3.2 WORKING PRINCIPAL: -

As shown in the figure, 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. Buton the other side when the magnetic material is removed from the magnetic field, the thermometer shows low temperature as its temperature decreases.

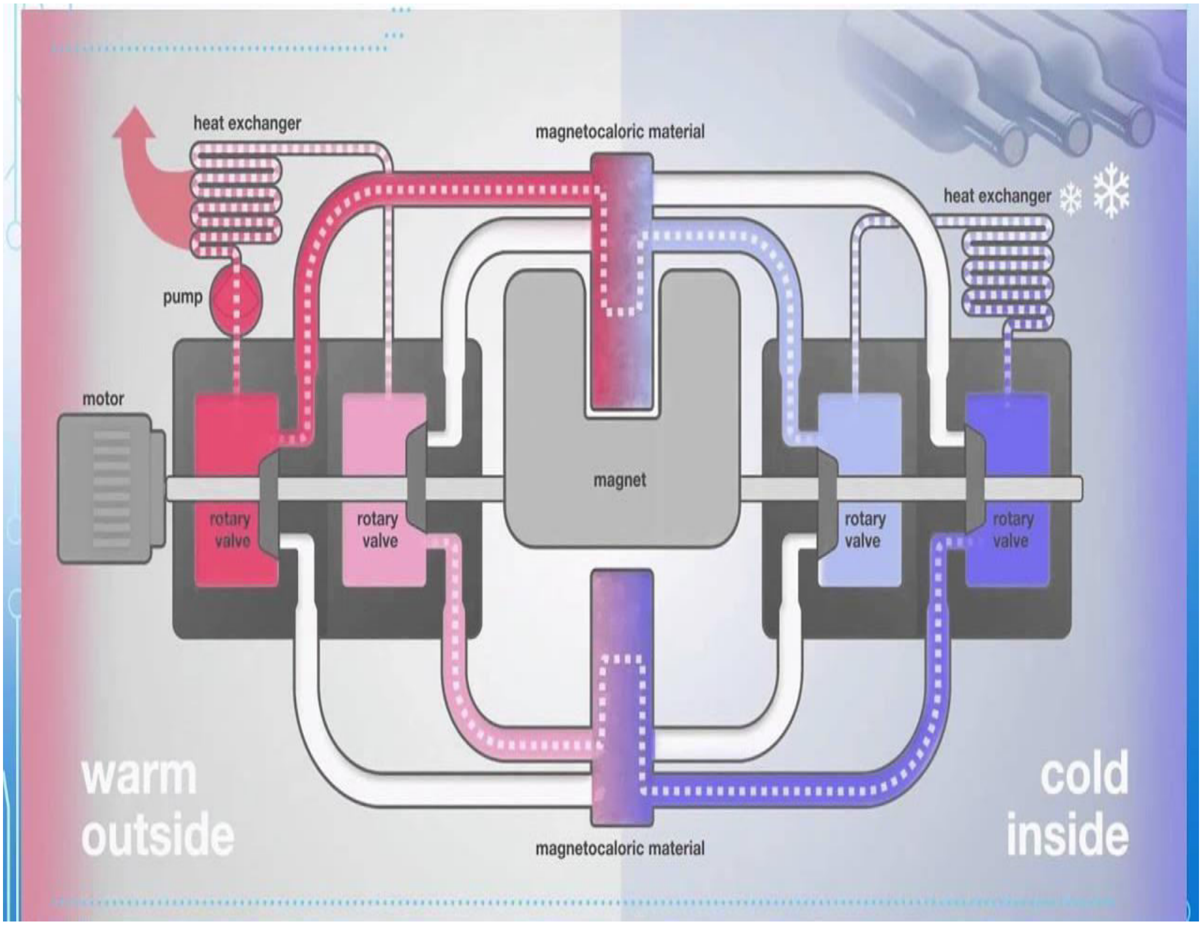

Fig.4: Working of Magnetic Refrigeration

3.3 Steps for thermodynamic cycle:

1. Adiabatic magnetization
2. **Isomagnetic enthalpy transfer**
3. Adiabatic demagnetization
4. **Isomagnetic entropic transfer**

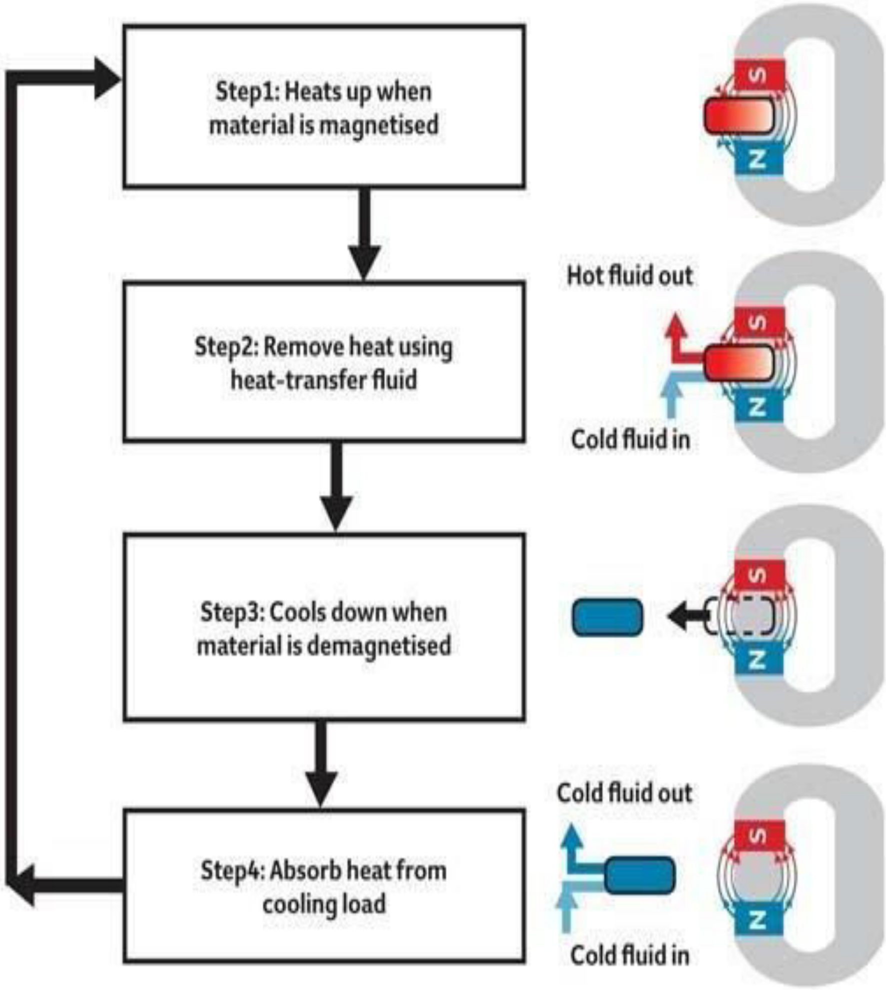

Fig.5: Thermodynamic Cycle

3.4 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.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 ($T + \Delta Tad$).

Isomagnetic enthalpy 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 Magnetic Refrigeration 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.

CHAPTER 4 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 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 analyse 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 Magnetic Refrigeration provides promise that magnetic refrigeration systems may be able to achieve higher efficiency than conventional liquefaction methods.

CHAPTER 5

5.1 Advantages:

- Magnetic refrigeration can be seen as an environmentally friendly alternative to conventional vapour-cycle refrigeration.
- Magnetic refrigeration is more compact.
- Magnetic refrigeration has higher reliability over VCR due to solid workingmaterials instead of gases.
- Fewer and most slow moving parts.
- Cost is high but running cost is 20% less
- Ozone depletion refrigerants are avoided.
- Efficiency is 60 to 70% to Carnot cycle.

5.2 Disadvantages:

- The initial investment is more as compared to conventional refrigeration.
- The magneto caloric materials are rare earth materials hence their availability also adds up as a disadvantage.
- MCE materials also need to be developed to allow higher frequencies forrectilinear and rotary magnetic refrigerators.
- Permanent magnets have limited field strength. Electromagnets and superconducting magnets are too expensive

5.3 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 household refrigeration appliances
  - Magnetic cooling and air conditioning in buildings and houses
  - Central cooling system
  - Refrigeration in medicine
  - Cooling in food industry and storage
  - Cooling in transportation
  - Cooling of electronics

CHAPTER 6

CONCLUSION

- It is a technology that has been proven to be environmentally safe.
- In order to make magnetic refrigerator commercially viable, scientists need to know how to achieve larger temperature swings and also permanent magnets which can produce strong magnetic fields of order 10T.
- There are still some thermal and magnetic hysteresis problems to be solved for materials that exhibit the MCE to become really useful.
- Magnetic materials available for room temperature magnetic refrigeration are mainly Gd, GdSiGe alloys, MnAs like materials, perovskite like materials.
- Excellent behaviour of regeneration and heat transfer is required.
- It can be used as household refrigerator, central cooling systems, room air conditioners and supermarket refrigeration applications.
- This technology must be universalized worldwide.

CHAPTER 7 REFERANCES

- http://en.wikipedia.org/wiki/Magnetic_refrigeration
- A text book on **cryogenic engineering** by V.J.Johnson
- "Refrigeration and Air conditioning" by Arora and Domkundwar
- **Magnetic Refrigeration**, ASHRAE Journal (2007), by John Dieckmann, Kurt Roth and James Brodrick

[1] T. Utaki1, K. Kamiya, T. Nakagawa1, T. A. Yamamoto1 and T. Numazawa,**"Research on a Magnetic Refrigeration Cycle for Hydrogen Liquefaction"** Cryocoolers 14, edited by S.D. Miller and R.G. Ross, Jr. International Cryocooler Conference, Inc.,
Boulder, CO, 2007

[2] Smt. Kinnari S. Damania, **"An Introduction to New Refrigeration Technology Magnetic Refrigeration"** IJSRD - International Journal for Scientific Research & Development| Vol. 3, Issue 07, 2015

[3] Yash Kulkarni, **"A Review on Magnetic Refrigeration at Room Temperature"** International Journal of Innovative Research in Science, Engineering and Technology (An ISO 3297: 2007 Certified Organization) Vol. 4, Issue 12, December 2015

[4] Dr. L.C.Singal, Aishna Mahajan, Rajwinder Singh, **"Magnetic Refrigeration-A Review- A boon for the coming generations"** SSRG International Journal of Mechanical Engineering (SSRG – IJME) – Volume 3 Issue 5 – May 2016

[5] K. Engelbrechta and C. R. H. Bahl, "**Evaluating the effect of magnetocaloricproperties on magnetic refrigeration performance"** JOURNAL OF APPLIED PHYSICS 108, 123918 (2010)