DEMONSTRATION OF MAGNETO CALORIC EFFECT BY FABRICATING A MAGNETIC REFRIGERATION SETUP

Sarvika Desai[1], Nikhil Kodiyal[1], TanazulIsrar[1], AkshayMulik[1], Thomas Mathewlal[2]
[1] Undergraduate Students, Mechanical Engineering Department
[2] Associate Professor, Mechanical Engineering Department
Fr. C. Rodrigues Institute of Technology, Vashi, Navi Mumbai

ABSTRACT
Modern society largely depends on readily available refrigeration methods. The conventional vapor compression refrigerators have mainly been used for refrigeration applications till now. Nonetheless, the conventional refrigerators – based on gas compression and expansion – are not very efficient because the refrigeration accounts for 25% of residential and 15% of commercial power consumption due to the use of high power consuming compressors. Moreover, Conventional Refrigerators utilize ozone depleting refrigerants like Freon which release CFCs, which have a detrimental effect on our environment.

Fabricating a model that produces a refrigeration effect by utilizing a green technology, namely Magnetic refrigeration is a novel concept. It incorporates the principle of the magneto-caloric effect and can act as a substitute for the conventional refrigerating systems. The elimination of compressors considerably reduces the power consumption and makes refrigeration a noiseless process, while the elimination of Freon makes it an environmentally friendly refrigerating technique. Magnetic Refrigeration set up is made with limited resources and experiments are conducted using substitutes of Gadolinium.

Keywords: Gadolinium, green technology, magneto caloric effect, magnetic refrigeration, temperature drop.

I. INTRODUCTION
Emil Gabriel Warburg (1846-1931), a German physicist, and a professor of physics at the Universities of Strassburg, Freiburg and Berlin, carried out extensive research in the areas of kinetic theory of gases, electrical conductivity, gas discharges, ferromagnetism and photochemistry. In 1881, he discovered the magneto-caloric effect in an iron sample. He noticed that when the iron sample was subjected to a magnetic field, its temperature increased and it decreased when moved out of the magnetic field.

This technology was successfully applied in low temperature physics to cool down samples from a few Kelvin to a few hundredths of a Kelvin above the absolute zero point (-273.15 K).

However, recently this concept has widely been applied to carry out the refrigeration process at room temperature and has proved to be highly profitable. In 1997, the first near room temperature demonstration of the concept of a magnetic refrigerator was conducted by Karl A. Gschneidner, Jr. by the Iowa State University at Ames Laboratory.

This study explains the Magneto-caloric concept in Magnetic Refrigeration and presents a new and simplified model to demonstrate the same using the limited resources.

II. PRINCIPLE OF MAGNETOCALORIC EFFECT
Magnetic Refrigeration works on the magneto-caloric effect, a magneto-thermodynamic phenomenon, in which a change in temperature of a suitable material is caused by exposing the material to a changing magnetic field. The cycle is performed as a refrigeration cycle, analogous to the vapor compression cycle (Fig 1). The magnetic material is the refrigerant in case of the magnetic refrigeration cycle. The process starts in thermal equilibrium with the refrigerated environment.

![Fig. 1 Analogy of Magnetic refrigeration to Vapor cycle refrigeration](image)
2.1 Adiabatic magnetization: In this process, a magneto-caloric substance is placed in an insulated environment and is subjected to an increasing external magnetic field (+H) (Fig 1). This causes the magnetic dipoles of the atoms to align themselves along the magnetic field, thereby decreasing the material's magnetic entropy and heat capacity. Since it is an adiabatic process, total entropy is not reduced (according to thermodynamic laws) as a result of which the item heats up to a temperature (T + ΔTad).

2.2 Isomagnetic enthalpic transfer: The heated magnetic material undergoes Isomagnetic enthalpic transfer where the added heat can then be removed (-Q) by a fluid or gas — like water, gaseous or liquid helium (Fig 1). During this process, the magnetic field is held constant to prevent the dipoles from reabsorbing the heat. Once sufficiently cooled, the magneto-caloric substance is moved out of the magnetic field (H=0) and is separated from the coolant.

2.3 Adiabatic demagnetization: The substance is returned to another adiabatic (insulated) condition so the total entropy remains constant. However the magnetic field is decreased. The thermal energy causes the magnetic moments to overcome the field, and thus the sample cools (an adiabatic temperature change) (Fig 1). Energy and entropy transfers from thermal entropy to magnetic entropy (disorder of the magnetic dipoles).

2.4 Isomagnetic entropic transfer: The magnetic field is held constant to prevent the material from heating back up during this process. The material is then placed in thermal contact with the environment being refrigerated. Because the working material is cooler than the refrigerated environment, heat energy migrates into the working material (+Q) hence producing the refrigeration effect (Fig 1).

III. WORKING MATERIALS

Gadolinium (Thermal conductivity k= 10.6W/mK) and its alloys are the best materials available today for magnetic refrigeration near room temperature since they undergo second-order phase transitions which have no magnetic or thermal hysteresis involved. However, moving away from rare earth metals, other materials including MnFeP\textsubscript{1-x}As\textsubscript{x} have distinct cost and scarcity advantages. The development of this technology is material dependent and most likely will not replace vapor-compression refrigeration without development of significantly improved materials that are cheap, abundant, and exhibit much larger magneto-caloric effects over a larger range of temperatures. Ultimately, these materials will also need to undergo significant temperature changes with a field around two tesla or less so that permanent magnets can be used for the production of the magnetic field. Other promising substitutes:

- \text{Gd}_{3} \text{(Si}_{0.60} \text{Ge}_{0.40})_{4}
- \text{La(Se}_{x} \text{Si}_{1-x})_{3} \text{H}_{x}
- \text{Gd}_{1+x} \text{Tb}_{LB}
- \text{Gd}_{2} \text{Si}_{2} \text{Ge}_{2}
- \text{La}_{0.66} \text{Ca}_{0.31} \text{Y}_{0.03} \text{MnO}_{3}
- \text{La}_{0.66} \text{Ca}_{0.31} \text{MnO}_{3}
- \text{MnFeP}_{1-x} \text{As}_{x}

IV. CONVENTIONAL MODEL AND SETUP

In 1970, Professor Brown developed a method to cool air at normal room temperature by using magneto-caloric effect. In 1990, Green and co-workers were the first to use the Magneto-caloric Effect for room- temperature cooling of a load other than the magnetic material using a setup as shown in Fig 2. Thereafter, from the late 1990s through the current decade, many active magnetic regenerator (AMR) cooling devices have been developed by various organizations around the world.

Fig. 2 Rotary Magnetic Cooler Developed by Astronautics Corporation of America\textsuperscript{[4]}

In the conventional magnetic refrigeration set up, the entire magneto-caloric wheel keeps rotating. The material or the refrigerant is placed inside the magneto-caloric wheel. The material inside the wheel is carried through different processes of thermodynamics due to the rotation of the wheel. The refrigeration effect is obtained by absorption of heat by the refrigerant in the hot heat exchanger.

V. CONSTRAINTS

An attempt was made to modify the design of the conventional magnetic refrigeration setup to meet the available resources. The accuracy and finishing of the components is limited due to the material properties and

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the machining process employed. Also, processes like casting introduce limitations for flexible designing and are hence excluded from our options of fabrication processes. The material selection for the modified model of the experimental setup is done taking into consideration the availability, cost and the material properties. Complexity of construction of the widely accepted magnetic refrigeration setup is eliminated by the use of simplified versions of heat exchangers. Experiments would be performed under atmospheric conditions as ideal and isolated conditions are not possible considering the limitations of the resources. A large experimental setup is not a viable option as it makes the apparatus bulky for domestic experiments. Hence, a modified model is designed based on the dimensions of a domestic vapor compression refrigerator so that it can be incorporated into any domestic refrigerator.

6.1. Casing:
The Modeling and 2D drawing of the casing was done on the software Coral Draw. The material used for fabrication of the casing is Acrylic as it has excellent insulating properties. Also the entire process can be monitored as it is transparent. The cutting of the acrylic sheet was carried out using the laser cutting machine as shown in Fig. 3. The curved portion of the casing was constructed by heating and bending the cut section of the acrylic sheet.

6.2. Motor:
An AC motor with variable speed is required for rotating the arm. The motor is mounted on an external arm from the casing as shown in the fig. 4. A nut is used to position the motor on the extended arm of the casing. The motor selected has a speed of 3.5 rpm when given a supply of 6 volts and is bi-directional. However the speed of the motor can be varied by changing the magnitude of the supply current using a variable voltage adapter.

6.3. Magnets:
The designing process incorporated the use of electromagnets so that the magnetic field could be varied as per requirement. However a Rectifier would be required to convert the AC supply to a DC supply. To avoid the use of rectifier, permanent magnets of 3000 Gauss power were used in the experiment. The magnets were stuck on the curved acrylic sheet as shown in the figure with the help of a strong adhesive. The magnets are rectangular in shape with the dimension 20mmX15mmX5mm as shown in fig. 5.

6.4. Heat Exchanger:
The heat exchanger is used to cool the heated material subjected to the magnetic field. Different mediums such as liquid helium can be used for heat exchange, however water is used in this experiment as it is easily available, non-toxic and convenient. Provision for the flow of water was done in the lower section of the casing.

6.5. Electronic Probe:
A Thermometer can be used for measuring temperature. But the drawback of using a thermometer is its inaccuracy in measurement and human error. Hence an
electronic probe was selected as shown in fig. 6. The electronic probe records the temperature at different sections. The range of the probe is from 0-75°C. The electronic probe is made of aluminum and it measures the temperature accurately up to the given range. It also possesses the ability to measure temperature at complex sections inaccessible to the thermometer.

6.6. Rotating Arm:
The rotating arm has a length of 150mm. It serves as the material carrier as shown in fig 7. The arm is fabricated from the acrylic sheet using the laser cutting machine. The slot for the entire circular motion of the arm is made by using a circular hand cutter. The evaporator section has rubber flaps covering the inlet and the outlet to provide the isolation.

Fig. 6 Electronic Probe

6.7. Assembly:
The components were attached together using an adhesive and Chloroform. The joints are all made water proof. Fig. 8 demonstrates the final Magnetic Refrigeration setup.

Fig. 7 Rotating Arm

The motor provides power to the magnetocaloric wheel, which enables the wheel to rotate in the anticlockwise direction. The motor rotates the arm and the arm in turn rotates the refrigerant which is clamped to it. It passethrough various sections of the casing undergoing the four processes of magnetic refrigeration.

An acrylic guideway with permanent magnets mounted along its periphery provides a continuous magnetic field. The permanent magnets stretch from the end point of hot heat exchanger and terminates at the end of cold heat exchanger. The magnetocaloric wheel is concentric with the permanent magnet wheel, as a result of which it is subjected to a constant magnetic field, paving way to adiabatic magnetization. The cold heat exchanger casing is filled with chilled water or coolant and is provided with inlet and outlet openings for continuous flow of water. This material at a state of high temperature enters this casing and transfers heat to the coolant. The coolant absorbs the heat from the refrigerant while it is under the influence of magnetic field resulting in the second process of isomagnetic enthalpy transfer. The material then enters the isolation casing. When the material enters this casing, it is shielded from the magnetic field and is subjected to conditions suitable for adiabatic processes. Magnetocaloric effect or adiabatic demagnetization takes place in this region and the refrigerant reaches freezing temperatures. The material enters the hot heat exchanger in the next stage. Refrigeration effect takes place in this particular section of casing. The casing is separated from the isolation casing by providing a partition, to ensure that complete heat exchange takes place. Air is isolated in this casing by means of rubber valves. The refrigerant enters this chamber and absorbs the heat, thus providing the refrigeration effect. The cycle repeats once the magnetocaloric wheel leaves the hot heat exchanger.
VII. EXPERIMENTAL RESULTS

Experiments were carried out using two substitutes En-31 and Copper. The following observations were noted.

OBSERVATIONS:
Ambient atmospheric temperature: 29.9°C
Dimensions of the materials used: 5mm X 5mm X 25.4 mm
Strength of the Magnetic Field: 3000 Gauss
Coolant in the Heat Exchanger: Water
Motor speed: 3.5 rpm
Observation duration:45 mins

Table-1

<table>
<thead>
<tr>
<th>SR. NO</th>
<th>MATERIAL</th>
<th>ADIABATIC MAGNETIZATION TEMPERATURE (°C)</th>
<th>EVAPORATOR TEMPERATURE (°C)</th>
<th>TEMPERATURE DIFFERENCE IN EVAPORATOR (°C)</th>
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</thead>
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<td>30.9</td>
<td>29.8</td>
<td>0.1</td>
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<tr>
<td>2</td>
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<td>29.8</td>
<td>0.1</td>
</tr>
<tr>
<td>3</td>
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<td>29.6</td>
<td>0.3</td>
</tr>
<tr>
<td>4</td>
<td>En-42</td>
<td>31.4</td>
<td>29.7</td>
<td>0.2</td>
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</table>

Further, we carried out experiments on the same materials, in the same environmental conditions using electromagnets and observed the following results:

Table-2

<table>
<thead>
<tr>
<th>SR. NO</th>
<th>MATERIAL</th>
<th>ADIABATIC MAGNETIZATION TEMPERATURE (°C)</th>
<th>EVAPORATOR TEMPERATURE (°C)</th>
<th>TEMPERATURE DIFFERENCE IN EVAPORATOR (°C)</th>
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</thead>
<tbody>
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<tr>
<td>4</td>
<td>En-42</td>
<td>32.1</td>
<td>29.6</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The above observations show limited results due to the following factors:
1) Imperfect isolation of the evaporator chamber.
2) The substitutes exhibited a very small Magneto-caloric effect due to the different domain structure.
3) The strength of the magnetic field was not enough for the materials selected for the experiment.
4) The material size was limited due to the weight constraint of the arm.
5) The medium used for the heat exchanger was water.

VIII. CONCLUSION

The Magneto-Caloric Effect was obtained by performing experiments on the new model. The apparatus demonstrated a better refrigeration effect for higher values of magnetic field provided by electromagnets. Although the observed temperature drop was less than expected, the obtained results can be improved. Other materials such as Gadolinium, Magnetite and Cobalt demonstrate a better magneto-caloric effect, and so they may be used to obtain better results. Perfect isolation can be provided by using rubber valves in the isolation chamber in order to minimize the inflow of heat from the atmosphere. Also, a better medium like brine solution may be used in the heat exchanger. Apart from these, the number of cycles of operation can be increased and the experiment can be carried out at a lower speed to obtain better results.

REFERENCES

[5] HoussemRafik El-Hana Bouchekara1,2 and Mouaaz Nahas1, Magnetic Refrigeration Technology at Room Temperature, Mentouri University – Constantine, Constantine, Saudi Arabia, Algeria.