STUDY OF ROOM TEMPERATURE MAGNETIC REFRIGERATION

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Abstract: In this paper Thermodynamic performance analysis for a magneto caloric material such as Gadolinium and Terbium is presented. Performance parameter is taken as magnetic entropy change and temperature change at constant room temperature, different magnetic fields. Furthermore the thermodynamic performance is compare between gadolinium and Terbium. Also, a study on the development of magnetic refrigerator at room temperature has been also carried out a model of Rotating Magnetic refrigeration has been developed. By use of MCE it is possible to create magnetic refrigerators—the machines where magnetic materials are used as working bodies instead of a gas, and magnetization/demagnetization is used instead of compression/expansion in conventional refrigerators. To realize any cooling process, it is necessary to have a system in which entropy depends on temperature and some external parameter. In the case of a gas this parameter is pressure, and in the case of a magnetic material it is magnetic field.

Index Terms- Magnetic Refrigeration, Revolution per minute, chlorofluorocarbon, Coefficient of performance, Magnet calor material, Ferro magnet, hydro chlorofluorocarbon, Permanent magnet, Magneto calor effect, Permanent magnet, Susceptibility, Magnetic entropy.

1 INTRODUCTION

1.1 Introduction

Modern society largely depends on readily available refrigeration methods. Up till now, the traditional fume pressure fridges have been mostly utilized for refrigeration applications.” Regardless, the ordinary coolers – in view of gas pressure and development – are not extremely productive in light of the fact that the refrigeration represents 25% of private and 15% of business power utilization.” [1] Moreover, using gases such as chlorofluorocarbons (CFCs) and hydro chlorofluorocarbons (HCFCs) have detrimental effects on our environment. As of late, the improvement of new innovations, for example, attractive refrigeration – has carried an option in contrast to the customary gas pressure procedure.

The attractive refrigeration at room temperature is a developing innovation that has pulled in light of a legitimate concern for scientists around the globe.” [2] Such a technology applies the magneto calor effect which was first discovered by Warburg in 1881. [3] Warburg noticed an increase of temperature when an iron sample was brought into an attractive field and a decline of temperature when the example was evacuated out of it. Thus, the magneto calor effect is an intrinsic property of magnetic materials; where it is defined as the response of a solid to an applied magnetic field which appears as a change in its temperature. [3] Such materials are called magneto calor materials. The magneto calor effect is present in all transition metals and lanthanide-series elements, which may have ferromagnetic behavior. When a magnetic field is applied, the magnetic moments of these metals tend to align parallel to it, and the thermal energy released in this process produces the heating of the sample. The magnetic moments become randomly oriented when the magnetic field is removed, thus the ferromagnetic metal cools down. [4] The ultimate goal of this technology would be to develop a standard refrigerator for home use. The utilization of attractive refrigeration can possibly decrease working and support costs when contrasted with the customary technique for blower based refrigeration. By eliminating the high capital cost of the compressor and the high cost of electricity to operate the compressor, magnetic refrigeration can efficiently (and economically) replace compressor-based refrigeration technology. Some potential points of interest of the attractive refrigeration innovation over the blower based refrigeration are:

1) Green innovation (no dangerous or opposing gas emanation);
2) Noiseless technology (no compressor);
3) Higher energy efficiency;
4) Simple design of machines;
5) Low maintenance cost; and low (atmospheric) pressure (this is an advantage in certain applications such as in air-conditioning and refrigeration units in automobiles). This section is worried about the attractive refrigeration innovation structure the material-level to the framework level. It gives a point by point audit of the attractive refrigeration models accessible as of not long ago. The operational standard of this innovation is clarified top to bottom by making similarity between this innovation and the ordinary one. The chapter also investigates the study of the magneto calorics materials using the molecular field theory. [4]

1.2 Development of Prototype Magnetic Refrigerators

The development of the magnetic refrigeration technology has followed the typical skewed “S” shape growth pattern (Fig. 1.1). At the beginning (between 1881 and 1930), after the discovery of the magneto calor effect, the development was very slow due to a lack of interest in this effect and its possible applications. In the following time frame, somewhere in the range of 1930 and 1975, the enthusiasm for attractive refrigeration among specialists began to increment. Around then, various huge papers were distributed, however completely centered around the cooling underneath 20 K. During the most recent 30 years, beginning with the year 1976 when Brown made the plan of the main model attractive refrigeration at room temperature, the advancement right now significantly extended. The number of papers has greatly increased but it has probably not reached its maximum yet. This will hopefully happen in the future, thus making the technology of magnetic refrigeration competitive to vapor compression.
Refrigeration Device. [5]

![Graph showing the number of developed magnetic refrigerators at room temperature per year.](image)

**Fig. 1.** The number of developed magnetic refrigerators at room temperature per year [5]

The most developed of the considerable number of models are the three gadgets made by Zimm et al. which seem to be setting the trend for the magnetic refrigeration development. [6], [7] A full review of room temperature magnetic refrigerators was undertaken by Gschneidner and Pecharsky. [5]

The magnetic refrigerator developed by the Laboratory for Refrigeration and the Laboratory for Modeling Machine Elements and Structures (both Faculty of Mechanical Engineering, University of Ljubljana) is based on revolving development of dynamic attractive regenerators (AMRs), set in a turning drum and the attractive field produced by perpetual magnets Nd-Fe-B. Using interfacing components made of delicate ferromagnetic material, four lasting magnets with center components inside and outside the pivoting drum make a solid and homogenous attractive field noticeable all around hole. On the perimeter of the turning drum, four air holes trade with four somewhat more extensive demagnetization regions with a low attractive field.

1.3 Magneto caloric Effect

For a better understanding of the magneto caloric effect and its application in magnetic refrigeration, let us consider an adiabatic system or an isolated magneto caloric material (Fig 1.2). When the magneto caloric material is not exposed to a magnetic field, the magnetic moments in the material are disordered or randomly orientated. However, when a magnetic field is applied, the magnetic moments become oriented in the direction of the applied magnetic field. From the magnetic point of view the system has reduced magnetic entropy ($S_m$), which means that in an adiabatic system the temperature of the material must increase [8]. A reverse process taking place is observed when the magneto caloric material from the magnetic field is removed, and the magnetic moments revert to random orientations. This causes an increase in the magnetic entropy and a corresponding decrease in the temperature. As a result, the system cools down. [9]

1.4 Magnetism and Matter

Magnetic phenomena are universal in nature. Vast, atoms, men and beasts all are permeated through and through with a host of magnetic fields from a variety of sources. The earth’s magnetism predates human evolution. The word magnet is gotten from the name of an island in Greece called magnesia where attractive metal stores were found, as ahead of schedule as 600 BC. Shepherds on this island whined that their wooden shoes (which had nails) on occasion remained struck to the ground. Their iron-tipped rods were similarly affected. These attractive distant galaxies, the tiny invisible property of magnets made it difficult for them to move around. [10]

![Scheme of magneto caloric effect.](image)

**Fig: 1.2** Scheme of magneto caloric effect [9]
1.4.1 Ideas Regarding Magnetism

- The earth behaves as a magnet with the magnetic field pointing approximately from the geographic south to the north.
- When a bar magnet is freely suspended, it points in the north-south direction. The tip which focuses to the geographic north is known as the North Pole and the tip which focuses to the geographic south is known as the south post of the magnet.
- There is a loathsome power when north posts (or south shafts) of two magnets are united close. On the other hand, there is an appealing power between the north shaft of one magnet and the south post of the other.
- We can't disconnect the north, or South Pole of a magnet. On the off chance that a bar magnet is broken into equal parts, we get two comparable bar magnets with to some degree more fragile properties. In contrast to electric charges, confined attractive north and south shafts known as attractive monopoles don't exist.
- It is conceivable to make magnets out of iron and its combinations.

1.4.2 The Earth’s Magnetism

Prior we have alluded to the attractive field of the earth. The strength of the earth’s magnetic field varies from place to place on the earth’s surface; its value being of the order of $10^{-5}$. The attractive field lines of the earth look like that of a (speculative) attractive dipole situated at the focal point of the earth. The axis of the dipole does not coincide with the axis of rotation of the earth but is presently tilted by approximately 11.3º with respect to the later. Right now taking a gander at it, the attractive posts are found where the attractive field lines because of the dipole enter or leave the earth. The location of the north magnetic pole is at latitude of 79.74º N and a longitude of 71.8º W, a place somewhere in north Canada. The attractive south shaft is at 79.74º S, 108.22º E in the Antarctica. [10]

1.4.3 Magnetic Properties of Materials

Classification of materials-Diamagnetic, Paramagnetic and Ferromagnetic. In terms of the susceptibility ($\chi$), a material is diamagnetic if $\chi$ is negative, paramagnetic if $\chi$ is positive and small, and ferromagnetic if $\chi$ is large and positive.

1.4.3.1 Diamagnetism

Diamagnetic substances are those which have propensity to move from more grounded to the more vulnerable piece of the outer attractive field. In other words, unlike the way a magnet attracts metals like cadmium, copper, silver, bismuth etc, it would repeal a diamagnetic substance.

1.4.3.2 Para Magnetism

Paramagnetic substances are those which get feebly polarized when set in an outer attractive field. They have tendency to move from a region of weak magnetic field to strong magnetic field, i.e., they get weakly attracted to a magnet, for example aluminum, calcium, and Oxygen etc.

1.4.3.3 Ferro Magnetism

Ferromagnetic substances are those which get strongly magnetized when placed in an external magnetic field. They have strong tendency to move from a region of weak magnetic field to strong magnetic field, i.e., they get strongly attracted to a magnet, For example cobalt, iron, nickel, Gadolinium, terbium, Neodymium etc.

The individual particles (or particles or atoms) in a ferromagnetic material have a dipole minute as in a paramagnetic material. Be that as it may, they collaborate with each other so that they unexpectedly adjust themselves a typical way over a plainly visible volume called area. The explanation of this cooperative effect requires quantum mechanics. Each domain has a net magnetization. Run of the mill area size is 1mm and the space contains around $10^{11}$ molecules. In the first instant, the magnetization varies randomly from domain to domain and there is no bulk magnetization. When we apply an external magnetic field $H''$, the domains orient themselves in the direction of $H''$ and simultaneously the domain oriented in the direction of $H''$ grow in size. This existence of domains and their motion in $H''$ are not speculations. One may watch this under a magnifying lens in the wake of sprinkling a fluid suspension of powdered. [10]
2 Literature Review
In this section, the magneto caloric effect will be introduced and described. The thermodynamic cycle of room temperature permanent magnet devices, the AMR, is presented

2.1 The Magneto caloric Principle
The magneto caloric effect displays itself in the emission or absorption of heat by a magnetic material under the action of a magnetic field. Under adiabatic conditions, a magnetic field can produce cooling or heating of the material as a result of variation of its internal energy. Also, the term “magneto caloric effect” can be considered more widely by its application not only to the temperature variation of the material, but also to the variation of the entropy of its magnetic subsystem under the effect of the magnetic field. [11]

2.1.1 M.A. Benedict (2017)
The main request attractive change material LaFeSiMn (H) is utilized to make multi-arrange regenerators to explore the significance of regenerator and magnet plan on magneto caloric refrigeration execution. [12]

2.1.2 Jeffrey Brock, Mahmud Khan (2017)
We report on the perception of enormous refrigeration limits close to room temperature in Ni$_x$Mn$_{1-x}$Cr$_y$In Heusler combinations. The alloys exhibit the L21 cubic crystal structure and undergo a second order ferromagnetic to paramagnetic phase transition. The individual Curie temperatures differ with Cr fixation from 315 K to 290 K. [13]

2.1.3 X.Q. Gaoa, J. Shena (2016)
A high weight crossover fridges that joins the dynamic attractive refrigeration impact with the Stirling cycle refrigeration impact at room temperature is concentrated here. In the mechanical assembly, a helium-gas-filled alfa-type Stirling cooler uses Gd sheets as the regenerator and the regenerator is placed in an attractive field shifting from 0 to 1.4 T, which is given by a Halbach-type turning lasting magnet get together. With an operating pressure of 5.5 MPa and a frequency of 2.5 Hz, a no-load temperature of 273.8 K was reached in 9 minutes, which is lower than that of 277.6 K for pure Stirling cycle. [14]

3 Problem Definition, Objectives and Methodology
3.1 Problem definition
The primary question to be answered by this study is: Can magnetic cooling be applied in the domestic environment and outperform traditional vapor compression systems?

In the state of the art, no extensive study regarding the applicability of magnetic cooling to domestic environments has been found. Thus, the aim of this thesis is to provide an assessment on the application of this promising technology to household refrigeration appliances. The two main refrigeration devices commonly found in the domestic environments are the refrigerator and the air conditioner. Thus, two cases have studied:
- Compare the thermodynamic performances between the refrigeration cycles using Gadolinium, Terbium as the working substances.
- Investigation of magneto thermal phenomena in magnetic materials is of great importance for solving fundamental problems of magnetism and solid refrigerant.

3.2 Objectives
The main objective of this work is to assess the viability of magnetic cooling for domestic applications and to assess their technical performance. In order to do so, the following objectives are set:
- The complete calculation of the thermodynamic parameter: entropy change and temperature change for Gd and Tb has to be carefully performed. This calculation is based on different magnetic fields $\Delta H = 0.5T$, $1.0T$, $1.5T$, $2.0 T$, $2.5T$ and $3.0T$.
- Compare the entropy change when working substance Gd and Tb separately.
- Compare the Temperature change when working substance Gd and Tb separates.

3.3 Methodology
To achieve these objectives, the thermodynamic performance analysis for a magneto caloric material in refrigeration cycle.

The dynamic setup is chosen because its ability to predict the performance of a refrigeration cycle system is superior to that of a stationary setup, as demonstrated in the setup works survey. The static model relies heavily in heuristic approximations, while a dynamic setup offers a more accurate and precise approximation; this allows the dynamic setup to offer a better approximation based on refrigeration cycle. [15]

The magneto caloric material data will be computed using the mean field model. The mean field theory describes the thermodynamic properties of a ferromagnetic material with acceptable accuracy. This provides smooth and thermodynamically consistent data for a variety of temperatures and magnetic fields; also, it can be used to calculate the thermodynamic data of different MCM Gadolinium and Terbium, thus a magnetic refrigeration cycle and its thermodynamic performance analyses. [16]

4 Magnetic Materials and Theoretical Calculation of Entropy Change, Temperature Change
4.1 Magnetic Materials for Magnetic Refrigeration
Unadulterated gadolinium might be viewed similar to the perfect substance for attractive refrigeration, similarly as the perfect gas is for ordinary refrigeration. Be that as it may, similarly as customary frameworks are generally not worked with perfect gases, attractive fridges will perform better. The following list of magneto caloric materials for application in magnetic refrigerators:
- Binary and ternary intermetallic compounds

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Gadolinium-silicon-germanium compounds
Manganites
Lanthanum-iron based compounds

Gadolinium and Terbium a rare-earth metal, exhibits one of the largest known magneto caloric effects. It was utilized as the refrigerant for a considerable lot of the early attractive refrigeration structures. The issue with utilizing unadulterated gadolinium as the refrigerant material is that it doesn't show a solid magneto caloric impact at room temperature. All the more as of late, be that as it may, it has been found that circular segment liquefied amalgams of gadolinium, silicon, and germanium are progressively productive at room temperature. The prototype magnetic material available for room temperature magnetic refrigeration is the lanthanide metal at the Curie temperature of Gd and Tb 294 K and 260.6K respectively. [3]

The practical magnitude of the magneto caloric effect is characterized by two parameters: Isotherm entropy variation (ΔSm) and adiabatic temperature change (ΔTad) when a magnetic field change is applied over the material. Traditionally, the ΔTad has been referred as the magneto caloric effect per se. In addition, the entropy variation gives an idea of how much heat we can draw per cycle.

Magnetic caloric materials can be divided in two great families:

- First order magnetic transition (FOMT) materials: These materials experience a simultaneous ordering of magnetic dipoles and a crystalline structure change associated with the transition. They commonly show thermal and magnetic hysteresis.
- Second order magnetic transition (SOMT) materials: The magnetic moments of these materials become aligned during the transformation. They present no hysteresis, no crystalline lattice change and the MCE is almost instantaneous, in the order of microseconds.

<table>
<thead>
<tr>
<th>Material</th>
<th>Transition type</th>
<th>Curie Temperature</th>
<th>Max. ΔTad (K)</th>
<th>Max. ΔSm (J/Kg K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gd</td>
<td>SOMT</td>
<td>293</td>
<td>6.3 (0 – 2T)</td>
<td>5.76(0-2T)</td>
</tr>
<tr>
<td>Gd0.74Tb0.26</td>
<td>SOMT</td>
<td>275</td>
<td>5.6 (0 – 2T)</td>
<td>6.0(0 – 2T)</td>
</tr>
<tr>
<td>Gd3Ge5Si2</td>
<td>FOMT</td>
<td>273</td>
<td>7.5(0 – 2T)</td>
<td>28.0(0–2T)</td>
</tr>
<tr>
<td>La(Fe4Si0.1)1.1H1.1</td>
<td>FOMT</td>
<td>290</td>
<td>7.0(0 – 2T)</td>
<td>30.0(0 – 2T)</td>
</tr>
<tr>
<td>MnAs</td>
<td>FOMT</td>
<td>318</td>
<td>13(0–5T)</td>
<td>35.0(0–5T)</td>
</tr>
</tbody>
</table>

Attending to the cost of the materials, gadolinium is often thought to be at a disadvantage because the raw substance is expensive in relation to other components. Even though this may seem correct, it does not take into account the fact that the manufacturing costs have also to be included. For most of the candidate magnetic refrigerants, as the Lanthanides, and Mn based alloys, its manufacturing requires long term anneals (>24 h), and sometimes more than one annealing step, in order to homogenize the sample.

When magnetic refrigerants are mass produced, tons of materials per day will be required; and the factory space and amount of high temperature vacuum equipment to carry out such processes will be enormous and require a huge capital investment, much more than what is needed for preparing Gd metal and alloys.

Taking into account the conforming processes, most of the magnetic refrigerant materials are inorganic compounds or brittle intermetallic compounds, difficult to manufacture in usable forms for high efficiency utilization, such as wires, screens or foils. Gadolinium is a ductile metal and can be easily fabricated into these forms. However, when using packed sphere or particle regenerator, gadolinium and the other compounds are at even odds.

An issue associated with the intermetallic Mn refrigerant containing as and/or P is the fact that both have high vapor pressures. This makes the handling of these elements in the production of the appropriate compound an additional challenge and will add additional costs in manufacturing the magnetic refrigerant alloy. Also, environmental concern associated with the toxic elements As, P and Sb requires that these elements are processed in special handling facilities, and may not be authorized by the environmental and health agencies of each country for the use in household magnetic refrigerators.

The presence of hysteresis in FOMT compounds is not as troublesome as it may appear, as long as it is small enough in relation to other components. Even though this may seem correct, it does not take into account the fact that the manufacturing requirements are significant and, as such, the material will not be utilized.

4.2 Calculation of Temperature and Entropy for Gadolinium and Terbium

The Temperature is dependence of total entropy for a simple ferromagnetic material at constant magnetic fields H’ and H”. The horizontal line show adiabatic temperature change and vertical line show isothermal entropy change.
4.2.1 Calculate the Change of Magnetic Entropy

Important characteristics of a magnetic material are its total entropy $S$ and the entropy of its magnetic subsystem $\Delta S_M$ (change of magnetic entropy). Entropy can be changed by variation of the magnetic field, temperature and other thermodynamic parameters. [17]

$$\Delta S_M(T, \Delta H) = N K_B \left[ \ln \frac{\sinh \frac{2J+1}{2} x}{\sinh \frac{1}{2} x} - x B_J(x) \right]$$

(4.1)

Where $B_J(x)$ is Brillouin Function and defined as bellow

$$B_J(x) = \frac{2x^{2J+1}}{2x^{2J}} \coth \left( \frac{2x^{2J+1}}{2x^{2J}} \right) - \frac{1}{2J} \coth \left( \frac{x}{2} \right)$$

(4.2)

4.2.1.1 Gadolinium (Gd)

Where $x = 0.931$, Purity of Gadolinium $J = 3.5$, total angular momentum of an atom [17]

And $N$ is No. of Magnetic atom, which is depends on magnetic field and room temperature.

$T$ is SI Unit of Magnetic Fields

$N$ is No. of Magnetic atom and

Put the given value in equation 4.2,

$$B_J(0.931) = \frac{2 \times 3.5 + 1}{2 \times 3.5} \coth \left( \frac{2 \times 3.5 + 1}{2 \times 3.5} \times 0.931 \right) - \frac{1}{2} \coth \left( \frac{0.931}{2} \right)$$

$$B_J(0.931) = 1.1428 \coth(1.1428 \times 0.931) - 0.14285 \coth(0.14285 \times 0.931)$$

$$B_J(0.931) = 1.1428 \times 1.27037 - 0.14285 \times 1.3222$$

$$B_J(0.931) = 0.37130$$

Case 1

When $H' = 0 T$, $H'' = 0.5 T$ and Gadolinium use as a solid refrigerant

$N = 3.361 \times 10^{24}$ [17]

All value put in the equation 4.2

$$\Delta S_M(T, \Delta H) = 33.61 \times 10^{-23} \times 1.380658 \times 10^{-23} \ln \frac{\sinh \frac{2 \times 3.5 + 1}{2 \times 3.5} \times 0.931}{\sinh \frac{1}{2 \times 3.5} \times 0.931} - 0.34568$$

$$\Delta S_M(T, \Delta H) = 46.4039 \left[ \ln \frac{\sinh 1.064}{\sinh 0.133} - 0.34568 \right]$$

$$\Delta S_M(T, \Delta H) = 46.4039 \left[ \ln \frac{\sinh 1.2764}{\sinh 0.133} - 0.34568 \right]$$

$$\Delta S_M(T, \Delta H) = 46.4039 \times 1.9128$$

$$\Delta S_M(T, \Delta H) = 88.76 \text{ J/kg/K}$$

Case 2

When $H' = 0 T$, $H'' = 1.0 T$ and Gadolinium use as a solid refrigerant

$$\Delta S_M(T, \Delta H) = 88.76 \text{ J/kg/K}$$
\[ N = 3.44 \times 10^{24}[17] \]

All value put in the equation 4.2

\[ \Delta S_M(T, \Delta H) = 34.4 \times 10^{23} \times 1.380658 \times 10^{-23} \left[ \ln \frac{\sinh \frac{2x+1}{2x+3} \times 0.931}{\sinh \frac{1}{2x+3} \times 0.931} - 0.931 \times 0.3713 \right] \]

\[ \Delta S_M(T, \Delta H) = 47.495 \left[ \ln \frac{\sinh \frac{1}{0.133}}{\sinh \frac{1}{0.133}} - 0.34568 \right] \]

\[ \Delta S_M(T, \Delta H) = 47.495 \left[ \ln \frac{0.13392}{0.13392} - 0.34568 \right] \]

\[ \Delta S_M(T, \Delta H) = 47.495 \times 1.9128 \]

\[ \Delta S_M(T, \Delta H) = 90.848 \text{ J/kg/K} \]

**Case 3**

When \( H' = 0 \), \( H'' = 1.5T \) and Gadolinium use as a solid refrigerant

\[ N = 38.06 \times 10^{24} \text{ at } 1.5T [17] \]

All value put in the equation 4.2

\[ \Delta S_M(T, \Delta H) = 38.06 \times 10^{23} \times 1.380658 \times 10^{-23} \left[ \ln \frac{\sinh \frac{2x+1}{2x+3} \times 0.931}{\sinh \frac{1}{2x+3} \times 0.931} - 0.931 \times 0.3713 \right] \]

\[ \Delta S_M(T, \Delta H) = 52.5475 \left[ \ln \frac{\sinh \frac{1}{0.133}}{\sinh \frac{1}{0.133}} - 0.34568 \right] \]

\[ \Delta S_M(T, \Delta H) = 52.5475 \left[ \ln \frac{0.13392}{0.13392} - 0.34568 \right] \]

\[ \Delta S_M(T, \Delta H) = 52.548 \times 1.9128 \]

\[ \Delta S_M(T, \Delta H) = 100.513 \text{ J/kg/K} \]

**Case 4**

When \( H' = 0 \), \( H'' = 2.0T \) and Gadolinium use as a solid refrigerant

All value put in the equation 4.2

\[ \Delta S_M(T, \Delta H) = 4.0459 \times 10^{24} \times 1.380658 \times 10^{-23} \left[ \ln \frac{\sinh \frac{2x+1}{2x+3} \times 0.931}{\sinh \frac{1}{2x+3} \times 0.931} - 0.931 \times 0.3713 \right] \]

\[ \Delta S_M(T, \Delta H) = 55.86 \left[ \ln \frac{\sinh \frac{1}{0.133}}{\sinh \frac{1}{0.133}} - 0.3457 \right] \]

\[ \Delta S_M(T, \Delta H) = 55.86 \left[ \ln \frac{0.13392}{0.13392} - 0.3457 \right] \]

\[ \Delta S_M(T, \Delta H) = 55.83342 \times 1.9128 \]

\[ \Delta S_M(T, \Delta H) = 106.850 \text{ J/kg/K} \]

**Case 5**

When \( H' = 0 \), \( H'' = 2.5T \) and Gadolinium use as a solid refrigerant

\[ N = 4.238 \times 10^{24} [17] \]

All value put in the equation 4.2

\[ \Delta S_M(T, \Delta H) = 42.38 \times 10^{23} \times 1.380658 \times 10^{-23} \left[ \ln \frac{\sinh \frac{2x+1}{2x+3} \times 0.931}{\sinh \frac{1}{2x+3} \times 0.931} - 0.931 \times 0.3713 \right] \]

\[ \Delta S_M(T, \Delta H) = 58.512 \left[ \ln \frac{\sinh \frac{1}{0.133}}{\sinh \frac{1}{0.133}} - 0.3457 \right] \]

\[ \Delta S_M(T, \Delta H) = 58.512 \left[ \ln \frac{0.13392}{0.13392} - 0.3457 \right] \]

\[ \Delta S_M(T, \Delta H) = 58.512 \times 1.9128 \]

\[ \Delta S_M(T, \Delta H) = 111.922 \text{ J/kg/K} \]

**Case 6**

When \( H' = 0 \), \( H'' = 3.0T \) and Gadolinium use as a solid refrigerant

\[ N = 4.3674 \times 10^{24} [17] \]

All value put in the equation 4.2

\[ \Delta S_M(T, \Delta H) = 43.674 \times 10^{23} \times 1.380658 \times 10^{-23} \left[ \ln \frac{\sinh \frac{2x+1}{2x+3} \times 0.931}{\sinh \frac{1}{2x+3} \times 0.931} - 0.931 \times 0.3713 \right] \]

\[ \Delta S_M(T, \Delta H) = 60.299 \left[ \ln \frac{\sinh \frac{1}{0.133}}{\sinh \frac{1}{0.133}} - 0.3457 \right] \]

\[ \Delta S_M(T, \Delta H) = 60.299 \left[ \ln \frac{0.13392}{0.13392} - 0.34568 \right] \]

\[ \Delta S_M(T, \Delta H) = 60.299 \times 1.9128 \]

\[ \Delta S_M(T, \Delta H) = 115.34 \text{ J/kg/K} \]

**4.2.1.2 Terbium (Tb)**

Where \( \chi = 0.931 \), Purity of Terbium

\[ J = 6.0 \text{, total angular momentum of an atom [18] } \]
And N is No. of Magnetic atom, which is depends on magnetic field and room temperature.
T is SI Unit of Magnetic Fields,
N is No. of Magnetic atom and

Put the given value in equation 4.2,

\[ B_1(0.931) = \frac{2 \times 6 + 1}{2 \times 6} \coth \left( \frac{2 \times 6 + 1}{2 \times 6} \cdot 0.931 \right) - \frac{1}{2 \times 6} \coth \left( \frac{1}{2 \times 6} \cdot 0.931 \right) \]

\[ B_2(0.931) = 1.0833 \coth(1.0833 \times 0.931) - 0.0833 \coth(0.0833 \times 0.931) \]

\[ B_3(0.931) = 1.0833 \coth(1.00855) - 0.0833 \coth(0.07755) \]

\[ B_4(0.931) = 1.0833 \times 1.0369 - 0.0833 \times 12.921 \]

\[ B_5(x) = 0.33952 \]

**Case 1**

When \( H' = 0 \), \( H'' = 0.5 \)T and Terbium use as a solid refrigerant

\[ N = 32.82 \times 10^4 \text{\cite{18}} \]

All value put in the equation 4.2

\[ \Delta S_M(T, \Delta H) = 32.82 \times 10^{23} \times 1.380658 \times 10^{-23} \ln \left( \frac{\sinh \frac{2 \times 6 + 1}{2 \times 6} \cdot 0.931}{\sinh \frac{1}{2 \times 6} \cdot 0.931} \right) - 0.931 \times 0.33952 \]

**Case 2**

When \( H' = 0 \), \( H'' = 1.0 \)T and Terbium use as a solid refrigerant

\[ N = 3.60386 \times 10^4 \text{\cite{18}} \]

All value put in the equation 4.2

\[ \Delta S_M(T, \Delta H) = 36.0386 \times 10^{23} \times 1.380658 \times 10^{-23} \ln \left( \frac{\sinh \frac{2 \times 6 + 1}{2 \times 6} \cdot 0.931}{\sinh \frac{1}{2 \times 6} \cdot 0.931} \right) - 0.931 \times 0.33952 \]

**Case 3**

When \( H' = 0 \), \( H'' = 1.5 \)T and Terbium use as a solid refrigerant

\[ N = 3.6654 \times 10^4 \text{\cite{18}} \]

All value put in the equation 4.2

\[ \Delta S_M(T, \Delta H) = 36.654 \times 10^{23} \times 1.380658 \times 10^{-23} \ln \left( \frac{\sinh \frac{2 \times 6 + 1}{2 \times 6} \cdot 0.931}{\sinh \frac{1}{2 \times 6} \cdot 0.931} \right) - 0.931 \times 0.33952 \]

**Case 4**

When \( H' = 0 \), \( H'' = 2.0 \)T and Terbium use as a solid refrigerant

\[ N = 3.89 \times 10^4 \text{\cite{18}} \]

All value put in the equation 4.2

\[ \Delta S_M(T, \Delta H) = 3.89 \times 10^{23} \times 1.380658 \times 10^{-23} \ln \left( \frac{\sinh \frac{2 \times 6 + 1}{2 \times 6} \cdot 0.931}{\sinh \frac{1}{2 \times 6} \cdot 0.931} \right) - 0.931 \times 0.33952 \]

**Case 5**

When \( H' = 0 \), \( H'' = 2.5 \)T and Terbium use as a solid refrigerant

\[ N = 4.102 \times 10^4 \text{\cite{18}} \]
When \( H' = 0T \), \( H'' = 0.5T \) and Terbium use as a solid refrigerant  
\( N = 4.24993 \times 10^3 \) [18]  
All value put in the equation 4.2  
\[ \Delta S_M(T, \Delta H) = 42.4993 \times 10^{23} \times 1.380658 \times 10^{-23} \left[ \ln \left( \frac{\sinh \frac{2x+1}{2x}}{\frac{2x+1}{2x}} \right) \right. \\
\left. \sinh \frac{1}{2x} \right] = 1 - 0.931 \times 0.33952 \]  
\[ \Delta S_M(T, \Delta H) = 58.677 \left[ \ln \left( \frac{\sinh \frac{1}{2x}}{\frac{1}{2x}} \right) \right. \right. \\
\left. \sinh \frac{1}{2x} \right] = 1 - 0.931 \times 0.33952 \]  
\[ \Delta S_M(T, \Delta H) = 58.677 \left[ \ln \left( \frac{1}{2x} \right) \right. \right. \\
\left. \sinh \frac{1}{2x} \right] = 1 - 0.931 \times 0.33952 \]  
\[ \Delta S_M(T, \Delta H) = 58.677 \times 2.41202 \]  
\[ \Delta S_M(T, \Delta H) = 141.53 \text{ J/kg/K} \]  

**4.2.2 Calculate the Change of Temperature**  
Allows some conclusions to be drawn about temperature change \( \Delta T(T, H) \) behavior and its relation to \( \Delta S_M \). It should be noted that the expression in curly braces increases exponentially. [17]  
\[ \Delta T(T, \Delta H) = T \left( \exp \left( \frac{\Delta S_M(T, \Delta H)}{C_H} \right) - 1 \right) \]  
Where \( T = 300 \text{K}, \) Room Temperature \( C_H \) is specific Heat at constant Magnetic field  

**4.2.2.1 Gadolinium (Gd)**  
**Case 1**  
When \( H' = 0T, H'' = 0.5T \) or \( \Delta H = 0.5T, \) \( T = 300 \text{K} \) and \( C_H = 154.123 \text{ J/kg/K} \) at \( \Delta H = 0.5T \) [19]  
Put the all value in equation 4.3  
\[ \Delta T(T, \Delta H) = 300 \left( \exp \left( \frac{154.123}{154.123} \right) - 1 \right) \]  
\[ \Delta T(T, \Delta H) = 300 \times 0.77874 \]  
\[ \Delta T(T, \Delta H) = 233.62 \text{ K} \]  
**Case 2**  
When \( H' = 0T, H'' = 1.0T \) or \( \Delta H = 1.0T \) \( And \ T = 300 \text{K} \) \( C_H = 157.468 \text{ J/kg/K} \) at \( \Delta H = 2.0T \) [19]  
Put the all value in equation 4.3  
\[ \Delta T(T, \Delta H) = 300 \left( \exp \left( \frac{157.468}{157.468} \right) - 1 \right) \]  
\[ \Delta T(T, \Delta H) = 300 \times 0.78056 \]  
\[ \Delta T(T, \Delta H) = 234.17 \text{ K} \]  
**Case 3**  
When \( H' = 0T, H'' = 1.5T \) or \( \Delta H = 1.5T \) \( And \ T = 300 \text{K} \) \( C_H = 173.7523 \text{ J/kg/K} \) [19]  
\[ \Delta S_M(T, \Delta H) = 100.513 \text{ J/kg/K} \]  
Put the all value in equation 4.3  
\[ \Delta T(T, \Delta H) = 300 \left( \exp \left( \frac{100.513}{173.7523} \right) - 1 \right) \]  
\[ \Delta T(T, \Delta H) = 300 \times 0.78333 \]  
\[ \Delta T(T, \Delta H) = 235K \]  
**Case 4**  
When \( H' = 0T, H'' = 2.0T \) or \( \Delta H = 2.0T \) \( And \ T = 300 \text{K} \) \( C_H = 182.932 \text{ J/kg/K} \) at \( \Delta H = 2.0T \) [20]  
Put the all value in equation 4.3  
\[ \Delta T(T, \Delta H) = 300 \left( \exp \left( \frac{182.932}{182.932} \right) - 1 \right) \]  
\[ \Delta T(T, \Delta H) = 300 \times 0.79337 \]  
\[ \Delta T(T, \Delta H) = 238.01 \text{ K} \]
Case 5
When $H' = 0T$, $H'' = 2.5T$ or $\Delta H = 2.5T$
And $T = 300 K$
$C_h = 190.04 J/kg/K$ at $\Delta H = 2.0T$ [20]
Put the all value in equation 4.3
\[
\Delta T(T, \Delta H) = 300 \left( \exp \left( \frac{111.922}{190.04} \right) - 1 \right)
\]
\[
\Delta T(T, \Delta H) = 300 \times 0.802075
\]
\[
\Delta T(T, \Delta H) = 240.62 K
\]

Case 6
When $H' = 0T$, $H'' = 3.0T$ or $\Delta H = 3.0T$
And $T = 300 K$
$C_h = 194.45 J/kg/K$ at $\Delta H = 3.0T$ [20]
Put the all value in equation 4.3
\[
\Delta T(T, \Delta H) = 300 \left( \exp \left( \frac{115.345}{194.45} \right) - 1 \right)
\]
\[
\Delta T(T, \Delta H) = 300 \times 0.8097
\]
\[
\Delta T(T, \Delta H) = 242.91 K
\]

4.2.2.2 Terbium (Tb)

Case 1
When $H' = 0T$, $H'' = 0.5T$ or $\Delta H = 0.5T$
And $T = 300 K$
$C_h = 178.76 J/kg/K$ at $\Delta H = 0.5T$ [21]
Put the all value in equation 4.3
\[
\Delta T(T, \Delta H) = 300 \left( \exp \left( \frac{178.76}{109.30} \right) - 1 \right)
\]
\[
\Delta T(T, \Delta H) = 300 \times 0.8431
\]
\[
\Delta T(T, \Delta H) = 252.92 K
\]

Case 2
When $H' = 0T$, $H'' = 1.0T$ or $\Delta H = 1.0T$
And $T = 300 K$
$C_h = 195.799 J/kg/K$ at $\Delta H = 1.0T$ [21]
Put the all value in equation 4.3
\[
\Delta T(T, \Delta H) = 300 \left( \exp \left( \frac{195.799}{122.815} \right) - 1 \right)
\]
\[
\Delta T(T, \Delta H) = 300 \times 0.84587
\]
\[
\Delta T(T, \Delta H) = 253.76 K
\]

Case 3
When $H' = 0T$, $H'' = 1.5T$ or $\Delta H = 1.5T$
And $T = 300 K$
$C_h = 198.99 J/kg/K$ at $\Delta H = 1.5T$ [21]
Put the all value in equation 4.3
\[
\Delta T(T, \Delta H) = 300 \left( \exp \left( \frac{198.99}{122.806} \right) - 1 \right)
\]
\[
\Delta T(T, \Delta H) = 300 \times 0.84669
\]
\[
\Delta T(T, \Delta H) = 254.008 K
\]

Case 4
When $H' = 0T$, $H'' = 2.0T$ or $\Delta H = 2.0T$
And $T = 300 K$
$C_h = 208.99 J/kg/K$ at $\Delta H = 2.0T$ [22]
Put the all value in equation 4.3
\[
\Delta T(T, \Delta H) = 300 \left( \exp \left( \frac{208.99}{122.842} \right) - 1 \right)
\]
\[
\Delta T(T, \Delta H) = 300 \times 0.85934
\]
\[
\Delta T(T, \Delta H) = 257.80 K
\]

Case 5
When $H' = 0T$, $H'' = 2.5T$ or $\Delta H = 2.5T$
And $T = 300 K$
$C_h = 219.359 J/kg/K$ at $\Delta H = 2.5T$ [22]
Put the all value in equation 4.3
\[
\Delta T(T, \Delta H) = 300 \left( \exp \left( \frac{219.359}{136.605} \right) - 1 \right)
\]
\[
\Delta T(T, \Delta H) = 300 \times 0.86404
\]
\[
\Delta T(T, \Delta H) = 259.2 K
\]

Case 6
When $H' = 0T$, $H'' = 3.0T$ or $\Delta H = 3.0T$
And $T = 300 K$
\( \Delta T(T, \Delta H) = 300 \left( \exp \left( \frac{141.53}{225.896} \right) - 1 \right) \)

\( \Delta T(T, \Delta H) = 300 \times 0.8711 \)

\( \Delta T(T, \Delta H) = 261.33 \, K \)

5 Results and Discussion

5.1 Change of Entropy of MCM

The value of maximum possible magnetic entropy change is calculated with the help of equation 4.1 and 4.2. Table 5.1 presents the magnetic field dependence of maximum entropy change for heavy rare earth metals in the field of 3.0T, change of entropy is calculated at room temperature. In case of Gadolinium \( J = 3.5 \) and in case of Terbium \( J = 6 \) so that Brillouin function is different for Gadolinium and Terbium but purity of rare earth metal is constant

<table>
<thead>
<tr>
<th>Rare earth metal</th>
<th>Change of entropy at different magnetic field, ( \Delta S_M ) (J/kg/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5T</td>
</tr>
<tr>
<td>Gd</td>
<td>88.76</td>
</tr>
<tr>
<td>Tb</td>
<td>109.3</td>
</tr>
</tbody>
</table>

According to fig. 5.1, Entropy change Gap between Gd and Tb line is Maximum (29.167 J/kg/K) at 1.0T magnetic field. Gd and Tb both line is sudden change the slope after 1.0T magnetic field. Both lines increase continuous. Average change entropy in the case of Gd is 102.37 J/kg/K. Average change of entropy in case of Tb is 126.62 J/kg/K

5.2 Change of Temperature of MCM

Table 5.2 shows the maximum possible value of magneto caloric effect (\( \Delta T \)) at constant room temperature, calculated by equation 4.3 on the basis of \( \Delta S_M \) values and calculated values are varies exponentially and \( C_H \) specific heat at constant enthalpy changes at different magnetic field. The specific heat is increases with respect to magnetic field so that change of Temperature is also increased with magnetic field.

<table>
<thead>
<tr>
<th>Rare earth metal</th>
<th>Change of Temperature at different magnetic field, ( \Delta T ) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5T</td>
</tr>
<tr>
<td>Gd</td>
<td>233.62</td>
</tr>
<tr>
<td>Tb</td>
<td>252.92</td>
</tr>
</tbody>
</table>
According to fig. 5.2, Temperature change Gap between Gd and Tb line is Maximum (19.67 K) at 2.0T magnetic field. Gd and Tb both line is sudden change the slope after 1.5T magnetic field. Both lines increase continuous. Average change temperature in the case of Gd is 237.38 K. Average change of temperature in case of Tb is 256.503 J/kg/K.

6 Discussions
The MCE of Gd is studied the most thoroughly in comparison with other magnetic materials terbium. Because gadolinium often serves as some standard of the magneto caloric effect, and MCE in new materials is usually compared with it, we decided to present its magneto caloric performance calculation in detail—see Table 5.1–5.2. In figure 5.1, the temperature change and entropy change dependences of heat capacity of Gd and Tb single crystal in different magnetic fields up to 3.0T are shown. The magnetic field has a pronounced effect on the anomaly — it is considerably broadened and shifted to higher temperature with increasing magnetic field, which is typical for ferromagnets.

Temperature change of Gd and Tb shown in table 5.2, in case of Gd and Tb at 3.0T is Maximum and Temperature changes increases from magnetic field 0.5T to 3.0T. Difference of Temperature change between Gd and Tb at 2.0T is Maximum (19.7K). Temperature change of Tb at every magnetic field is Maximum from Gd.

Entropy change of Gd and Tb shown in table 5.1, in case of Gd and Tb at 3.0T is Maximum and entropy changes increases from magnetic field 0.5T to 3.0T. Difference of Entropy change between Gd and Tb at 1.0T is Maximum (29.167 J/kg/K). Entropy change of Tb at every magnetic field is Maximum from Gd.

7 Conclusions
On the basis of calculation, a numerical comparison of the main thermodynamic performances of these materials (Gd and Tb) individually and it is use as solid refrigerant in magnetic refrigerator, are evaluated and analyzed.

- Temperature change of Gd is Maximum (3.01K) when magnetic field change from 1.5T to 2.0T
- Entropy change of Gd is maximum (9.665 J/kg/K) when magnetic field change from 1.0T to 1.5T
- Average deviation in temperature change of Gd is 1.858
- An average deviation in Entropy change of Gd is 5.316
- Temperature change of Tb is Maximum (3.792K) when magnetic field change from 1.5T to 2.0T
- Entropy change of Tb is maximum (10.715 J/kg/K) when magnetic field changes from 0.5T to 1.0T.
- An average deviation in temperature change of Tb is 1.682K.
- Average deviation in Entropy change of Tb is 6.446 J/kg/K.
- On the basis of data is provided above, it can be concluded that Thermodynamic performance of Tb is better than Gd.

Reference: