ISSN: 2321-8169
582 – 588

Study of Magnetic Refrigerator Based on AMR Cycle

Hardik V. Shah[1], Rahul M. Shahapure[2], Prof. P.D. Menghani[3], Prof. V.P. Sawant[4]

[1]*Student, Department of Mechanical Engineering, Smt. Kashibai Navale College of Engineering, Pune, India,* ***hardiks099@gmail.com***
[2]*Student, Department of Mechanical Engineering, Smt. Kashibai Navale College of Engineering, Pune, India,* ***rahulshahapure@gmail.com***
[3]*Professor, Department of Mechanical Engineering, Smt. Kashibai Navale College of Engineering, Pune, India,****pankajk7391@gmail.com***
[4]*Professor, Department of Mechanical Engineering, Smt. Kashibai Navale College of Engineering, Pune, India,* ***vikram.sawant417@gmail.com***

ABSTRACT

We should preserve the environmental balance of planet earthwhile achieving peace and development of society. Today's society is faced by crisis relating to supply of energy, water, food, etc. Refrigeration is an important factor in the twenty first century. It is important in our day-to-day life for conversation of food, medicine, blood and preservation of human organs and tissues. However, refrigerationhas a negative effect on the environment and hence, refrigeration systems are subject to development. This advancement provides a great opportunity for the emergence of modern refrigeration technologies and new product for international markets. In upcoming years, magnetic refrigeration is considered as a serious alternative for conventional vapour compression systems. Today proof of the concept is established. This report reviews AMR (Active Magnetic Regenerative) refrigeration technology for low temperature applications that is a safe cooling method to expand the temperature span of magnetic refrigerators based on AMR cycle.

Keywords: (AMR) Active magnetic refrigerator cycle, ADR (Adiabatic Demagnetization Refrigerator), (MCE) Magneto-caloric effect

---

1. INTRODUCTION

Refrigeration is a process of moving heat from one location to another in controlled conditions for the purpose of lowering temperature of enclosed space or substance and maintaining the same low temperature. This heat transport is conventionally driven by vapour compression or absorption cycles, but can also be driven by ammonia, HFOs), thermal electric refrigeration, thermal acoustic refrigeration and magnetic refrigeration (MR). Applications of refrigerationinclude household refrigerators, industrial freezers, cryogenics, and air conditioning. In most developed countries, cities are mostly dependent upon refrigeration in supermarkets, houses in order to meet their daily needs.

The refrigeration industry achieved a major success with the developments of refrigerants like CFC-R12, HCFC-R22 (1935) and CFC-R502 (1961), HFC R134 (1993), etc. The complex HFCs do not deplete the ozone layerhowever; they still have some global warming potential impact (GWP). An idealrefrigerant must be environmentally safe, chemically stable, materially compatible with high refrigeration-cycle performance, non-flammability and non- toxicity etc. Modern refrigeration techniques are focused on two most important drawbacks. Firstly the depletion of the ozone layer (CFC, HCFC), secondly the intensification of greenhouse gases (CFC, HCFC and HFC) which increases carbon footprints.

In order to avoid these toxic refrigerants, industries are developing environmentally friendly and suitable new technologies that will enable high-energy savings, therefore reducing indirect CO2 emissions.

Active magnetic refrigeration system is considered as a dynamic alternative for conventional vapour compression refrigeration systems.

2. MAGNETIC REFRIGERATION

Magnetic refrigerationtechnology based on the magneto caloric effect, an intrinsic property of certain magnetic solids. The magnetocaloric effect is characterised by a temperature change induced by applying reversible magnetic field. It requires the combination of a magnetic source of rather high strength and a material with sufficiently high refrigerant capacity.The refrigerant is placed in apotentially strong magnetic field, forcing its various magnetic dipoles to align and putting these degrees of freedom of the refrigerant into a state of lowered entropy. The heat released by the refrigerant due to its loss of entropy is then absorbed by the heat sink. To ensure that the system is insulated the magnetic field is switched off andthermal contact with the heat sink is then

 ISSN: 2321-8169
582 – 588

broken. This increases the heat capacity of the refrigerant, which results in decreasing its temperature below the temperature of the heat sink.
Chemically rare earth element gadolinium and some of its alloys possess the magnetocaloric effect. Gadolinium's temperature rises when it is placed in certain magnetic fields. When it leaves the magnetic field, the temperature drops.
Equation:
The magnetocaloric effect can be quantified with the equation below:

$$\Delta T_{ad} = -\int_{H0}^{H1} \left(\frac{T}{C(T,H)}\right)_H \left(\frac{\partial M(T,H)}{\partial T}\right)_H dH$$

Where,
T: temperature,
H: applied magnetic field,
C: heat capacity of the working magnet (refrigerant)
M: magnetization of the refrigerant.
From the equation, we can see that magnetocaloric effect can be enhanced by:
1. Applying a large field,
2. Using a magnet with a small heat capacity,
3. Using a magnet with a large change in magnetization vs. temperature, at a constant magnetic field.

3. MAGNETO-THERMODYNAMIC CYCLE

The magneto-thermodynamic cycle is analogous to the Carnot refrigeration cycle, but with increases and decreases in magnetic field strength instead of increases and decreases in pressure.
1. Adiabatic magnetization: A magnetocaloric substance is placed in an increasing external magnetic field. The magnetic dipoles of the atoms align and decrease the material's magnetic entropy and heat capacity. This increases the temperature of the substance.
2. Isomagnetic enthalpy transfer: This added heat can then be removed with the help of a water based fluidor liquid helium. To prevent the dipoles from reabsorbing the heat the magnetic field is held constant by supplying constant energy. The magnetocaloric substance and the coolant are separated when equilibrium is achieved between them.
3. Adiabatic demagnetization: The substance is returned to another adiabatic condition to maintain constant entropy. This time the magnetic field is decreased and the thermal energy causes the magnetic moments to overcome the field due to which the sample cools, i.e. an adiabatic temperature change. Heat energy (and entropy) transfers from thermal entropy to magnetic entropy according to the intensity of MCE.
4. Isomagnetic entropic transfer: The reheating of the material is prevented by supplying constant energy to the magnet. Heat energy is transferred from the environment to be cooled to the material, which placed in thermal contact. Because the refrigerant is cooler than the refrigerated environment (by design), heat energy migrates into the working material.Once the refrigerant and refrigerated environment are in thermal equilibrium, the cycle restarts.

4. ACTIVE MAGNETIC REGENERATORS

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:
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

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:
1. Tubes
2. Perforated plates
3. Wire screens
4. Particle beds

ISSN: 2321-8169
582 – 588

5. KEY COMPONENTS OF AMR REFRIGERATOR

Brown developed a room temperature magnetic heat pump where a porous Gadolinium plate structure was used with water–alcohol mixture as heat transfer fluid inside the regenerator as shown in Fig-1 (left). Simple ADRs have been successfully used in many sub-Kelvin temperature applications and multi-stage ADRs have been developed to optimize the design for their cooling demand. ADR is the basic form of magnetic refrigerator shown in Fig-1(right) (a). However, its operating temperature span is limited to few Kelvin due to low intensity of material's magneto-caloric effect and weak magnetic field. An AMR cycle operates much faster than that of a typical ADR because of its simple construction. Nevertheless, it requires an efficient heat transfer mechanism between the magnetic refrigerant and its surroundings to achieve wide temperature range. As shown in Fig-1 (right) (b), an AMR core is located inside the magnet for cyclic magnetization and demagnetization to complete the magneto thermodynamic cycle. Heat exchangers situated near the warm and cold ends of the AMR to allow efficient heat exchange between the AMR and its surroundings.

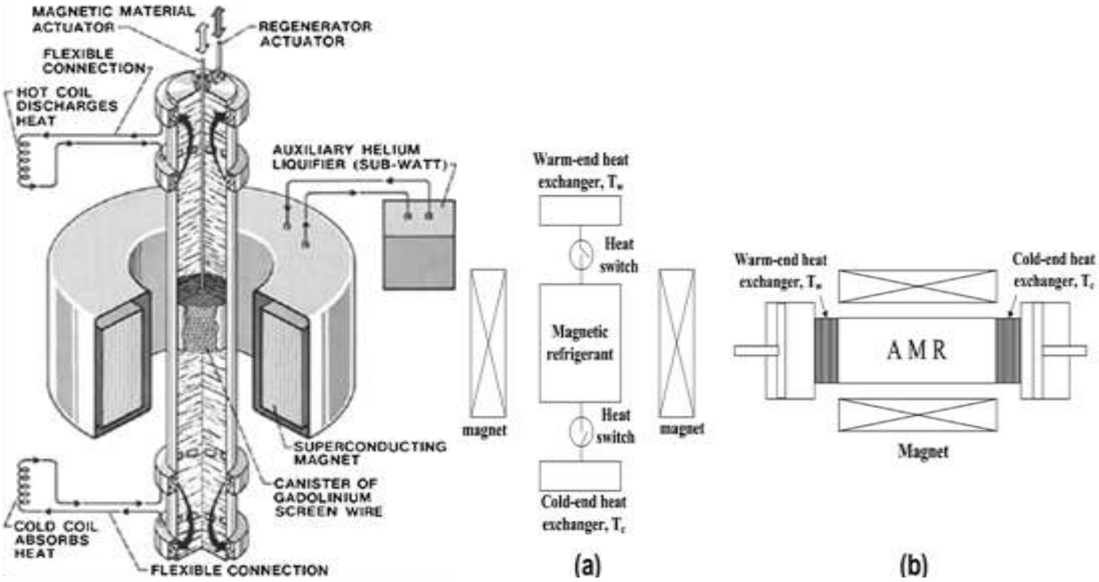

Fig-1: (left) AMR apparatus for room temperature magnetic refrigeration
(right) Schematic diagram of ADR and AMR (a) ADR (Adiabatic Demagnetization Refrigerator)
(b) AMR (Active Magnetic Regenerative) refrigerator.

5.1 Magnetocaloric material

This is the key component of any magnetic refrigeration, which fundamentally enables transferring heat from low temperature to high temperature. Paramagnetic and ferromagnetic materials near Curie temperature show large magneto-caloric effect and are useful to obtain wide temperature ranges. AMR has conceived to operate in a wide temperature span above or including the Curie temperature. The useful temperature span of a certain magneto-caloric material is characterised by magnetic field change. The gadolinium metal and its alloys are mainly used material in room temperature magnetic refrigerators.
Table 1 provides a review of magnetic materials that can be potentially used for magnetic refrigeration. The characteristics like phase transition temperature, the material type, and its applicability have been listed in the table. We still need more innovation in material science to develop a practical system to theoreticallycover the required temperature range from cryogenic to room temperature by AMR refrigeration.

No.	Substance	Tc[a] (K)	Materialcharacteristic	Applicability
1	Dy3Ga5O12(DG	0.37	Garnet, high thermalconductivity	Good candidate for AMR (2–12 K)
2	Gd3Ga5O12(GG	0.85	Garnet, high thermalconductivity	Excellent magnetic refrigerant below 10K
3	Gd3Al5O12(GAG		Garnet,highthermalconductivity,difficulttomakeintheformo single crystal	
4	Gd3(Ga0.8Al0.2		Garnet, solid solution of GAG andGGG	
5	Gd2(SO4)3	<1	Lighter thanGGG	Good for temperatures below 1.8K
6	Dy2Ti2O7	1.35	Available in powder form	Temperature range (4.2–20K)
7	HoPO4	1.39	RXO4[b]family	
8	TmVO4	2.15	RXO4[b]family, high thermalconductivity	
9	Dy3Al5O12(DAG	2.53	High thermalconductivity	Better than GGG above 10K
10	DyVO4	3.0	RXO4[b]family	Mixed with GGG in AMR machine between 2 K 20K
11	DyPO4	3.39	RXO4[b]family	

 ISSN: 2321-8169
582 – 588

12	$TmAsO_4$	6.0	RXO_4[b]family	Good material in the temperature range 5–10K
13	$ErNi_2$	6.7	Ferromagnetic rare-earth intermetalliccompound	Promising material in the wide below 35 K
14	$ErAl_2$	11.7	Ferromagnetic rare-earth intermetalliccompound	Useful for compound material for Ericsson type machine above 15K
15	$HoNi_2$	12.3	Ferromagnetic rare-earth intermetalliccompound	Promising material in the wide below 35 K
16	EuS	16.0	Ferromagnetic rare-earthcompound	PromisingmaterialforAMRmachineabove20K
17	$DyNi_2$	19.3	Ferromagnetic rare-earth intermetalliccompound	Promising material in the wide below 35 K
18	$HoAl_2$	26.8	Ferromagnetic rare-earth intermetalliccompound	Useful compound material for AMR machine 15K
19	$(Ho_{0.5}Dy_{0.5})Al$	46	Ferromagnetic rare-earth intermetalliccompound	Useful compound material for AMR machine 15K
20	$DyAl_2$	55.9	Ferromagnetic rare-earth intermetalliccompound	UsefulforAMRmachinebetween20Kand77K
21	Ho_5Si_4	76	Ferromagnetic rare-earth intermetalliccompound	
22	$GdNi_2$	85	Ferromagnetic rare-earth intermetalliccompound	Promising material in the wide
23	$(GdEr)_{0.5}Al_2$	96	Compound of $GdAl_2$ and$Er_{0.5}Al_2$	
24	Dy_5Si_4	140	Ferromagnetic rare-earth intermetalliccompound	
25	$GdAl_2$	164	Low hysterisismaterial	
26	$GdAl_{1.9}Ni_{0.1}$	191	Ferromagnetic rare-earth intermetalliccompound	
27	Gd_3In	213	Ferromagnetic rare-earth intermetalliccompound	
28	Tb_5Si_4	225	Ferromagnetic rare-earth intermetalliccompound	
29	Gd_3Al_2	287	Ferromagnetic rare-earth intermetalliccompound	Candidate for room temperature AMR
30	Gd	293	Puremetal	PopularmaterialforroomtemperatureAMR
31	MnP	298	Ferromagnetic compound	Candidate for room temperature AMR
32	Gd_5Si_4	336	Ferromagnetic rare-earth intermetalliccompound	Candidate for room temperature AMR

[a]Phase transitiontemperature.

[b]Rare earth material, X = V, As or P.

Table-1: Potential magnetic materials for a magnetic refrigerator

5.2 Magnet

Strong magnetic field is very importantto create large magneto-caloric effect with a given magnetic material. A superconducting magnet in either steady or varying modes depending on whether the system is dynamic or staticcan be able to generate the required magnetic field. A steady-fieldsuperconducting magnet, economical in terms of electric power control, needs cyclic displacement between the AMR and the magnet to generate magnetization and demagnetization. The superconducting magnet has to generate a time-varying field. The electric energy stored in the energized superconducting magnet should be regenerated to avoid unnecessary power loss by controlling electric power supply to the superconducting magnet. The AC loss should beminimum if the magnet is cooled by a cryocooler.

5.3 Heat exchanger

An AMR refrigerator requires two heat exchangers; one at the cold end where it cools down the area to be refrigerated and the other at the warm end where the heat is rejected to the higher temperature environment. A water-based fluid or helium gas is circulated throughout the system to transfer heat between AMR and the heat exchangers. If there is too much volume between the AMR core and the heat exchangers, this results intoinefficient heat rejection process at the warm end heat exchanger and an absorption process at the cold end heat exchanger. The heated fluid by AMR at the end of magnetization period may return to the AMR core without rejecting its heat to the warm end heat sink. Therefore, the heat exchanger should have high thermal effectiveness to minimize the dead volume between the AMR and the heat exchanger. Thermal construction of the heat exchanger in an AMR refrigerator is critical for large temperature span. Desirable temperature span will not be achieved due to unnecessary entropy generation during heat exchange process. It is difficult to calculate what the minimum effectiveness of the heat exchanger in AMR should be, because it depends on the system requirement. The ineffectiveness of the heat exchanger ultimately becomes the burden of the AMR whose performance characteristics are influenced by the system parameter such as the AMR size and the magnetic field strength, the magneto-caloric effect of the refrigerant and required temperature span. In general, the effectiveness value higher than 0.9 is recommended as a cryogenic heat exchanger although in some case, a 98% effective heat exchanger was used at liquid helium temperature.
In Fig-3, an example of the obtained temperature span between hot and cold sources, after a number of AMR cycles is demonstrated.

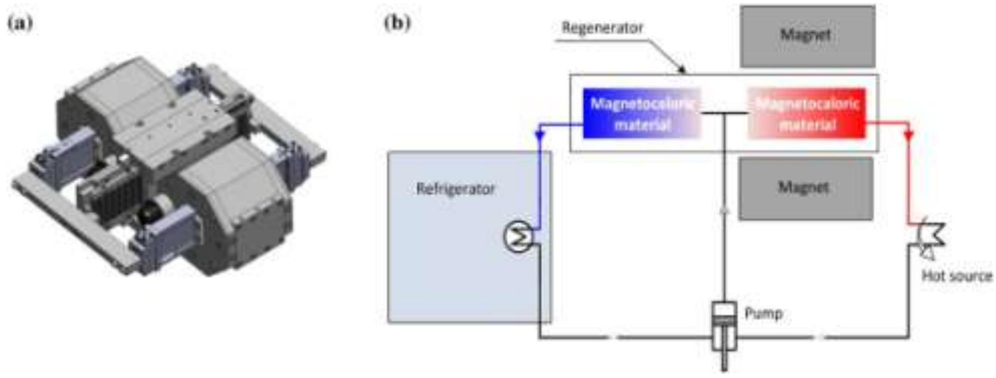

Fig-2:A general view of the developed magnetic refrigerator (a), and a schematic picture of the implemented AMR cycle with the new design of the regenerator (b).

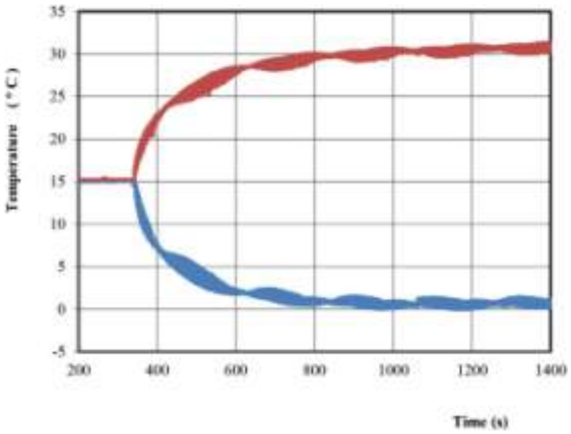

Fig-3:Example of the obtained temperature span

6. ADVANTAGES

Magnetic cooling is becoming a practical and advanced solution for the cold industry. The technology resolves the two main issues affecting the compressor-based refrigeration systems, the environmental challenge via a gas-free solution, and the economic challenge by reducing energy consumption and increasing the efficiency.
Since Montreal protocol (1987), many works have been carried out in order to eliminate the ozone depletion effect (Table-2). With Kyoto protocol (1997), energy efficiency has emerged as an important parameter in refrigerators.

1. High efficiency: As the magneto caloric effect is highly reversible, the thermodynamic efficiency of the magnetic refrigerator is high. It is somewhat 50% more than vapour compression cycle.
2. Reduced operating cost: As it eliminates the most inefficient part of today's refrigerator i.e. compressor. The cost reduces as a result.
3. 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 vapour compression cycles.
4. Reliability: Due to the absence of gas, it reduces concerns related to the emission into the atmosphere and hence is reliable one.
5. Ozone depleting refrigerants are avoided in this system, hence it more eco-friendly.
6. The efficiency of magnetic refrigeration is 60% to 70% as compared to Carnot cycle.

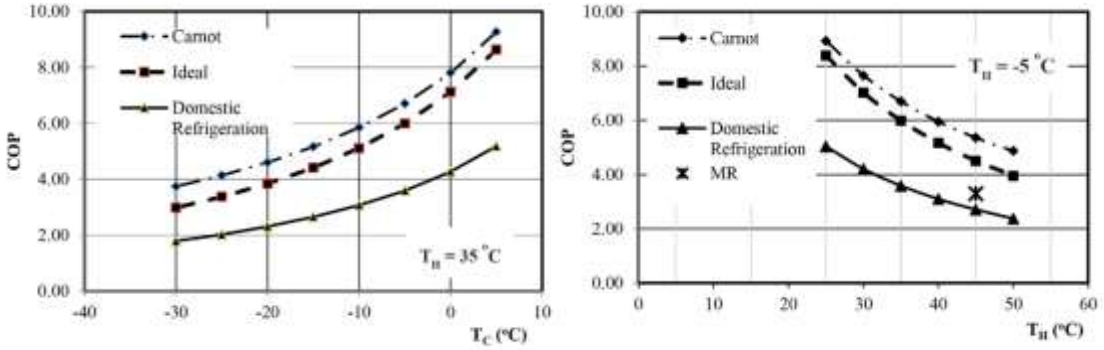

Fig-4:COP as a function of temperature in the case of conventional (R134a) and magnetic Refrigeration (MR) systems

Refrigerants	EnvironmentalO		Energyefficiency	Economicalcomparison	Toxicity/inflammability	
	DP	GWP	Volume capacity (ref.CFC-R12)	%eCHF/Kg (ref. HCFC R22,2012)	ATELtoxicity	LFL inflammabilitylimitlimit
CFC-R12	1	10,890	100		0.018	0.00
HCFC-R22	0.05	1810	161	100	???	0.00
HFC-R134a	0	1430	96	60	0.25	0.00
HFO-R1234yf	0	4	106	70	0.101	0.107
Ammonia	0	0	160	10	0.00035	0.104
HC-R290	0	3	140	64	0.09	0.038
CO_2-R744	0	1	840	26	0.036	0.00

Table-2: A list of refrigerants used in conventional cooling systems.

7. DISADVANTAGES

The use of gadolinium as active material has various disadvantages. First, the price of Gd is very high (w4000 $/kg). Second, Gd has a poor resistance to corrosion and oxidation in water, which affects its magnetocaloric properties, and de- creases the magnetic cooling machine performance. Finally, the cooling range is limited close to the room temperature where the magnetocaloric effect is very large (because of the second order transition occurring at 294K.

1. The initial investment is more as compared with conventional vapour compression refrigeration.
2. The magneto caloric materials are rare earth materials hence their availability also adds up a disadvantage in magnetic refrigeration.
3. GMCE materials need to be developed to allow higher frequencies of rectilinear and rotary magnetic refrigerators
4. Protection of electronic components from magnetic fields. However, notice that they are static, of short range and may be shielded
5. Permanent magnets have limited field strength. Electromagnets and superconducting magnets are expensive.
6. Eddy current heating losses can occur within the device due to the presence of the time-varying magnetic field and metallic materials.

8. CONCLUSION

If we say future perspectives of room temperature magnetic refrigeration, it can be seen from the earlier description that main progress have been made in America. However, with the continual phasic progress of room temperature magnetic refrigeration, the whole world has accelerated in the research. Nevertheless, it is notable that main work is concentrated on investigations of magnetic materials, lack of experimental explorations of magnetic refrigerator. From the former results achieved by researchers, it can be seen that there is still a great performance difference between magnetic refrigerator and vapour compression refrigerator in terms of cooling capacity and temperature span. At the end of this study, we can say:

1. This technology has proven to be environmentally safe.
2. In order to make the magnetic refrigerator commercially viable, scientists need to know how to achieve larger temperature swings and permanent magnets which can produce strong magnetic fields of order 10 tesla.
3. There are still some thermal and magnetic hysteresis problems to be solved for the materials that exhibit the MCE to become useful.
4. Magnetic materials available for room temperature magnetic refrigeration are mainly Gd, Gd alloys, per
5. Materials under development for room temperature magnetic refrigeration are La(fexsi1-X)13 and La(Fe0.88Si0.12)13Hy

ISSN: 2321-8169
582 – 588

6. Excellent behaviour of regeneration and heat transfer is required
7. It can be use household refrigerator, central cooling systems, room air conditioners and supermarket refrigeration applications.

ACKNOWLEDGEMENT

This review paper on “Study of Magnetic Refrigerator Based on AMR Cycle” is outcome of guidance, moral support and devotion bestowed on me throughout my work. For this I, acknowledge and express my profound sense of gratitude and thanks to everybody who have been a source of inspiration during the seminar preparation.

First, I offer our sincere phrases of thanks with innate humility to Mr. Pankaj Menghani Sir, my seminar guide who helped to me whenever needed and guided me throughout my work so that the report completion could be carried right within time. I would also like to thank my college Smt. Kashibai Navale College of Engineering (Mechanical Department), for providing such a stimulating atmosphere and wonderful work environment.

REFERENCES

[1]. Osmann Sari*, Mohamed Balli, “From conventional to magnetic refrigerator technology” Institute of Thermal Engineering, University of Applied Sciences of Western Switzerland, Avenue des Sports 20, 1400 Yverdon-les-Bains, Vaud, Switzerland

[2]. Thomas Burdyny*, Andrew Rowe “Simplified modeling of active magnetic regenerators” Department of Mechanical Engineering, Institute for Integrated Energy Systems, University of Victoria, 3800 Finnerty Rd, Victoria, B.C. V8W 3P6, Canada

[3]. Sangkwon Jeong “AMR (Active Magnetic Regenerative) refrigeration for low temperature” Cryogenic Engineering Laboratory, Department of Mechanical Engineering, School of Mechanical, Aerospace and Systems Engineering, Korea Advanced Institute of Science and Technology, Guseong-dong, Yuseong-gu, Daejeon 305-701, Republic of Korea

[4]. Magnetic Refrigeration, ASHRAE Journal (2007), by John Dieckmann, Kurt Roth and James BrodrickGschneidnerjr, K. A.; Pecharsky, V. K.; Tsokol, A. O. "Recent developments in magnetocaloric materials". Reports on Progress in Physics.

[5]. Aprea, C.; Greco, A.; Maiorino, A.; Masselli, C. (2016). "The energy performances of a rotary permanent magnet magnetic refrigerator". International Journal of Refrigeration.

[6]. Gibson, Kerry. "Magnetic Refrigerator Successfully Tested: Ames Laboratory developments help push boundaries of new refrigeration technology".

[7]. "Cooltech Applications". Cooltech Applications. Retrieved 2014-06-04.

[8]. http://www.basf-new-business.com/en/projects/e-power-management/solid-state-cooling/"Premiere of cutting-edge magnetocaloric cooling appliance". BASF. Retrieved 16 July 2015.