Chapter 1

Introduction

Refrigeration:

Our society is highly dependent on cooling technology. The cooling is used for preservation of foods, for different types of surgeries, for air conditioning, for different manufacturing processes. Refrigeration consumes the large part of energy supply of the world. There are different types of cycles used to obtain the required temperatures. One of them is most efficient, mature and reliable cycle is vapour compression cycle. Vapour compression cycle uses hazardous chemicals as refrigerant like CFC'S. This cycle is reached to its highest energy limit. The performance of this cycle cannot be increased. This system requires a compressor, which requires large amount of mechanical power and also vibrations, noise are carried along with it. The COP of this cycle is 40% of Carnot COP. The refrigerant contributes to environmental problems like ozone layer depletion and global warming.

Magnetic refrigeration is emerging technology in field of refrigeration. This system uses a magnetic solid material as a refrigerant. Magnetocaloric effect is the basis of the magnetic refrigeration. Magnetic material expels the heat when it is magnetized and absorbs the heat when it is demagnetized. By using this effects a lower temperatures are obtained. For room temperature magnetic refrigeration, magnetic field is produced by permanent magnet, which does not require power like electromagnets. Power requirement is also very small as compared to VCR. COP of this cycle is also large as compared to vapour compression cycle. So this is energy efficient technology. As concerned to environmental effect, society needs clean and energy efficient technology. Magnetic refrigeration technology is satisfies this need. This technology doesn't have ozone depleting and green house effects. This technology is environmental friendly.

Advantages

- High energy efficiency
- Low maintenance cost
- Green technology (no use of conventional refrigerants)
- Low pressure system (atmospheric pressure)
- Noiseless technology (no compressor), this is advantageous in certain applications like medical field

Chapter 2

Magnetic materials

2.1 Magnetocaloric effect:

Magnetocaloric effect or adiabatic temperature is defined as heating or cooling of the magnetic material due to application of magnetic field. Warburg first experienced Magnetocaloric effect in iron. Debye and Giuague suggested first use of this for adiabatic demagnetization.

Total entropy of magnetic material is function of magnetic field (H) and temperature (T). Total entropy of magnetic material is sum of magnetic entropy, lattice entropy and electronic entropy.

$$S\,(H, T) = S_M\,(H, T) + S_L\,(H, T) + S_E\,(H, T)$$

When magnetic field (H) is applied to magnetic material, magnetic entropy (S_M) of system changes due to alignment of magnetic moments of atoms. If the field is applied adiabatically, magnetic entropy of substance decreases. To keep total entropy of system constant, lattice (S_L) and electronic entropy (S_E) of system increases, causing heating of substance. If magnetic field is removed adiabatically, magnetic material gets cooled. When magnetic field (H) is applied isothermally (T = constant), total entropy (S) of system decreases because magnetic entropy of the system decreases

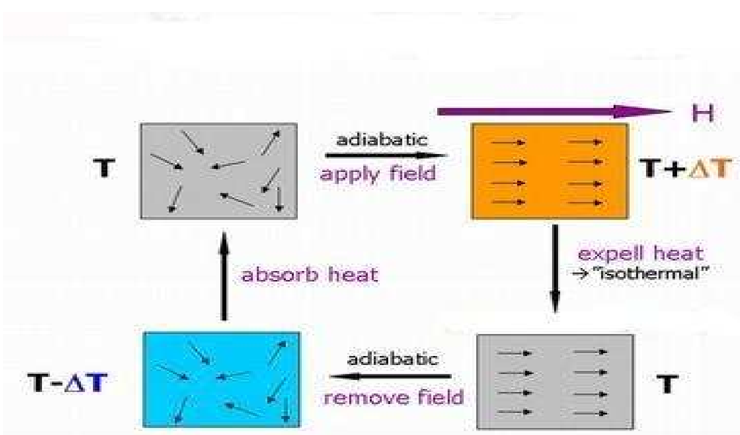


Figure 2- 1 Magnetocaloric effect [www.ifw-dresden.de]

Both ΔTad and ΔS_M are the characteristic values of Magnetocaloric effect and are function of magnetic field change and initial temperature. By increasing the field, magnetic order of the material increases and hence magnetic entropy decreases which results positive change in ΔTad and negative change in ΔS_M. Reversible change will occur if magnetic field is decreased.

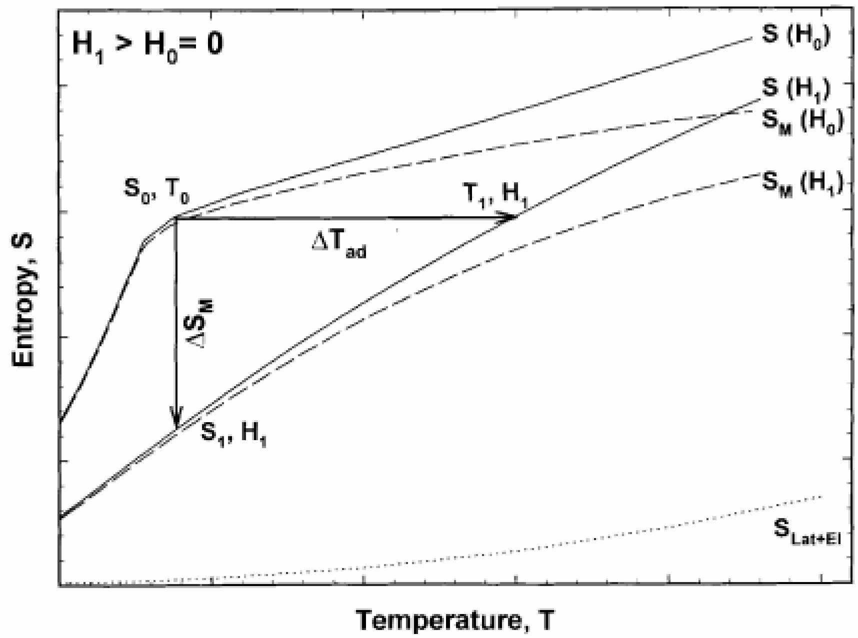


Figure 2- 2 S-T diagrams showing the Magnetocaloric effect, solid lines shows total entropy in two different magnetic field, dashed lines shows magnetic entropy in two fields and dotted lines shows combined lattice and electronic entropy. ΔTad and ΔS_M are due to change in magnetic field from H_0 to H_1 [1]

Adiabatic temperature change and isothermal entropy change are the quantitative measurements of Magnetocaloric effect. These are given by following equation [2]

$$\Delta S_M(T,\Delta H) = \int_{H1}^{H2} \left(\partial M / \partial T\right)_{H,P} dH$$

$$\Delta T(T,\Delta H) = -\mu_0 \int_{H1}^{H2} T / C_{H,P} \left(\partial M / \partial T\right)_{H,P} dH$$

1. Magnetization at constant field in both paramagnets and ferromagnets decreases with increase in temperatures hence ΔTad should be positive and ΔS_M should be negative for positive field changes.

2. In ferromagnets absolute value of change of magnetization with temperature is maximum at T_C hence ΔS_M should maximum at $T=T_C$
3. For same ΔS_M, the value of ΔTad will be larger at higher temperature and low heat capacity.

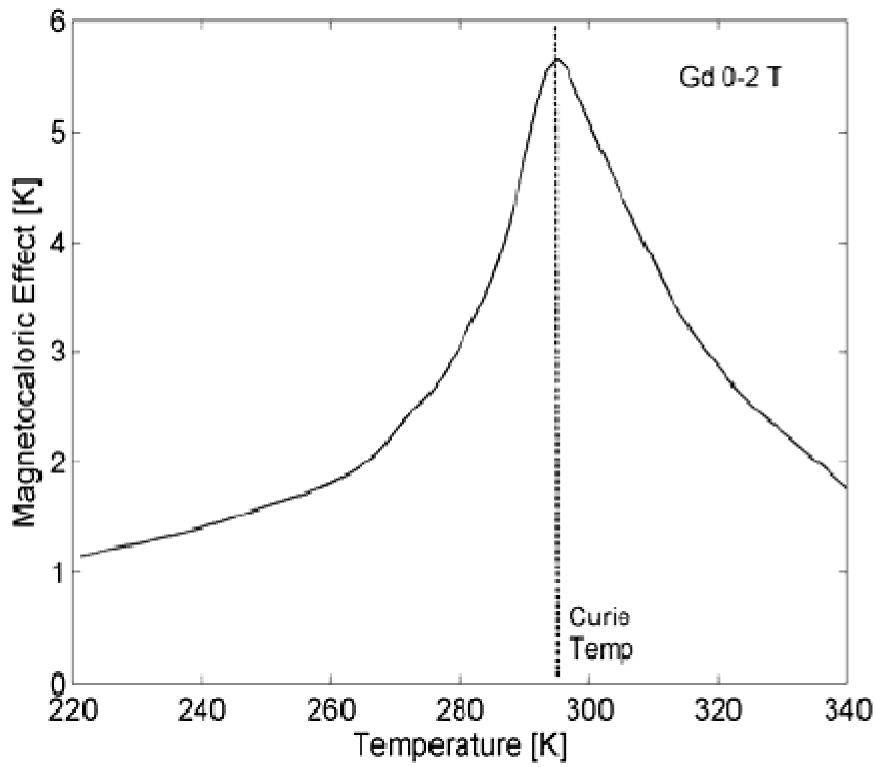


Figure 2- 3 Magnetocaloric effect in Gd on 0-2 T magnetic fields

2.2 MCE in order disorder magnetic phase transition:

When ferromagnetic substance is magnetized, its magnetic entropy decreases i.e. it orders magnetically. When this happens, magnetization strongly varies in a narrow temperature range, which allows large MCE. This temperature is called as Curie temperature. The material that orders at room temperature is Gadolinium. Its curie temperature is 294 K. Gd shows ΔTad at T_C are 6, 12, 16, 20 K for ΔH = 2.5, 7.5, 10 T.

many different alloys with Gd are studied to improve MCE in T_C , but they lowers the T_C or MCE. The only intermetallic material where MCE approaches Gd is Gd_5Si_5 with the $T_C \approx 335$ K.[1]

2.3 First order phase transition materials:

In magnetic order-disorder phase transition, magnetization is large at very narrow range of temperatures around Curie temperature. Some materials orders through first order magnetic phase transition, which is coupled with change of crystal structure. The first order phase transition occurs at constant temperature and derivative of magnetization with temperature may be infinitely large giving rise to giant magnetocaloric effect. $Gd_5Si_2Ge_2$ shows the magneto-structural phase transition. As shown in fig 2.3, MCE reaches 60 % of maximum value for μ_0H= 2 T in GMCE materials whereas only 40 % of maximum value for μ_0H= 2 T in conventional materials. [2]

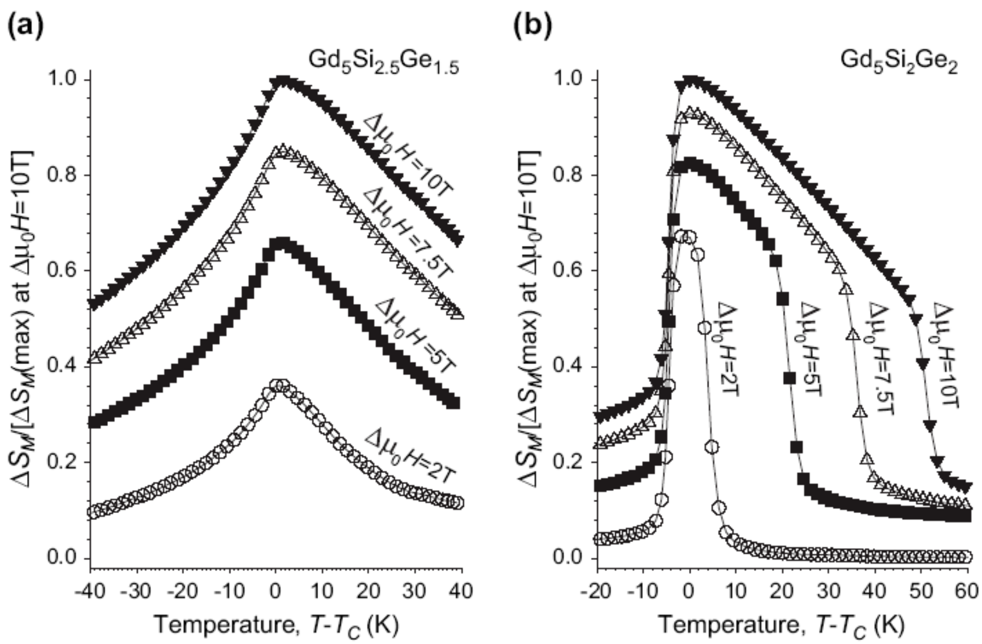


Figure 2- 4 Examples of (a) behavior of the magnetocaloric effect for conventional ferromagnet orders through order-disorder phase transition (b) behavior of magnetocaloric effect for ferromagnet orders through first order magneto-structural phase transition and in either case MCE is normalized to its maximum value at T_C for 10 T magnetic field strength, temperature is shown relative to T_C , which is 312 K in (a) and 270 K in (b) [2]

Chapter 3

Magnetic refrigeration

3.1 Magnetic refrigeration:

As mentioned above, Magnetic refrigeration uses magnetocaloric material as refrigerant. By changing the magnetic field, refrigeration effect is achieved. Magnetic field is supplied by the superconducting magnet, electromagnet or permanent magnet. Superconducting magnets requires liquid helium or liquid nitrogen, so use of this for practical application is unrealistic. Electromagnet requires electricity for their functioning. And permanent magnet does not require any of this. Permanent magnets can produce magnetic field of strength 2T. Using superconducting magnets produces high magnetic fields. Due to its advantages, this is fast growing technology.

3.2 Magnetic Ericsson cycle:

For practical refrigeration, temperature drop must be higher. But adiabatic temperature is very small when magnetic field is applied by permanent magnet. So to achieve large temperature drop regeneration is used. In this cycle regeneration is used. There are two isofield and two isothermal processes. Brown constructed first room temperature magnetic refrigerator based on Ericsson cycle. It consists of a vertical tube containing regenerator fluid (water or alcohol) and refrigerant in the form of parallel plates. The Gd is used as refrigerant. Refrigerant slides down the regenerator so that fluid passes through the plates. Two heat exchangers are placed at the ends of regenerator which exchange heat with surrounding and cooling load.

1. Isothermal magnetization (A-B): in this process, magnetic field is applied to the refrigerant when it at top. Heat is exchanged with surrounding.
2. Isofield cooling process (B-C): refrigerant and magnet is moved down and it exchange heat with fluid until its temperature decreases to cold end temperature.
3. Isothermal demagnetization (C-D): magnet is moved up so that field is removed. The temperature of bed decreases. It exchanges heat with bottom end heat exchanger, where it takes the heat load.

4. Isofield heating process (D-A): refrigerant is moved up in zero magnetic field, and it absorbs the heat from regenerator fluid.

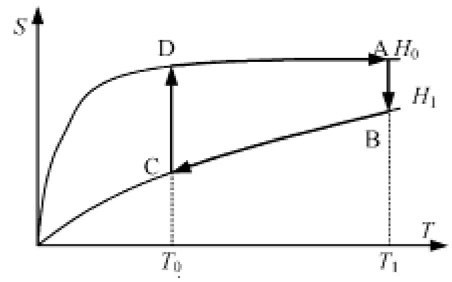


Figure 3- 1 Magnetic Ericsson cycle [6]

With this type of design and a superconducting magnet with a field of 7 T, he achieved a no load temperature difference 47 K between hot and cold ends. This is approximately three times the ΔTad of Gd in 7 T.

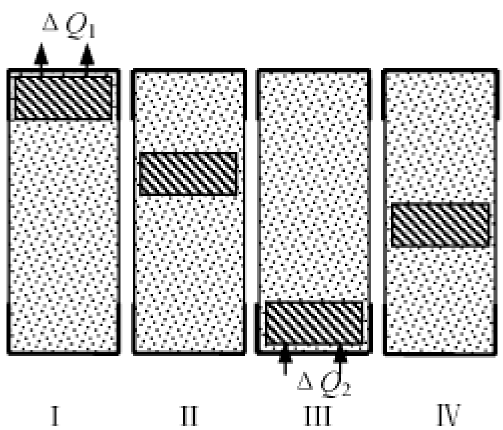


Figure 3- 2 principle of magnetic Ericsson cycle [3]

3.3 Active magnetic regeneration refrigeration:

The adiabatic temperature change is very small because of low magnetic field strength. For continuous magnetic refrigeration, different cycles are devised, but the temperature span is very small. Hence these cycles can not be used. To achieve larger temperature span, active magnetic regeneration refrigeration (AMMR) is used. In this, a porous packed bed of magnetic material is exposed to time varying magnetic field and time varying flow of heat transfer fluid. The AMMR concept has allowed magnetic cooling to be extended to near room temperature by removing the limitation on the overall temperature swing. Typically applied field variation is achieved by moving the AMR in-out magnetic field either linearly or rotationally. In AMR, magnetic material acts as a magnetic refrigerant and regenerative substance. [3]

Developments in active magnetic refrigeration:

Navy Laboratory built the first AMR device in 1980's at Annapolis. In this magnetic field is slowly charged by a superconducting magnet and heat transfer fluid is gas. But cooling capacity of such device is small. Then Reciprocating AMR was developed in which AMR is moved in out of magnetic field and water is used as heat transfer fluid. The cooling capacity of such is much better. Two such devices were demonstrated, one with 300W by astronautics collaborating with Ames laboratory in 1997 and second 100 W Toshiba and Chubu electric in Japan in 2000. These AMR requires high magnetic field and for that superconducting magnets are used. Reciprocating AMR uses superconducting magnets, which required maintaining at low temperature, by using cryocooler and power requirement to run the cryocooler is very large in comparison with cooling effect produced. Operating frequency of these is small (0.16 Hz), so size is very large. Also large forces are needed to withdraw the AMR from high magnetic field. Astronautics Corporation of America constructed a rotary active magnetic regenerator refrigerator in 2001.

3.3.1 Reciprocating active magnetic regenerator:

An AMR is based on a regenerator which allows fluid to flow through it. Different regenerator geometries are parallel plates or packed bed of particles. The regenerator is immersed in fluid in an enclosure and pistons at both ends of the enclosure can displace the fluid through the regenerator. Fluid transfers the heat from and to regenerator. A heat exchanger (CHEX) is placed at one end absorbs the heat from the cooling load. Another heat exchanger (HTEX) is placed at other end, rejects heat to the ambient. AMR moves in and out of the magnetic field to produce the MCE. AMR produces refrigeration effect in cyclic process and after certain number of cycles steady state is reached. There is linear temperature profile across the bed from CHEX to HTEX as shown in fig. Working cycle of AMMR is explained below.

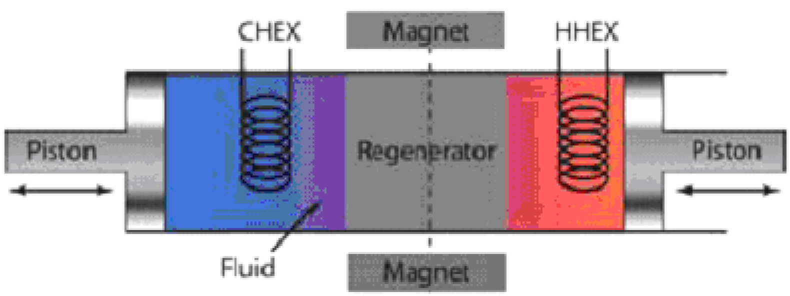
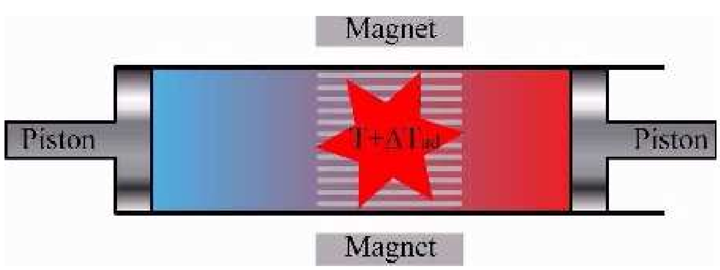
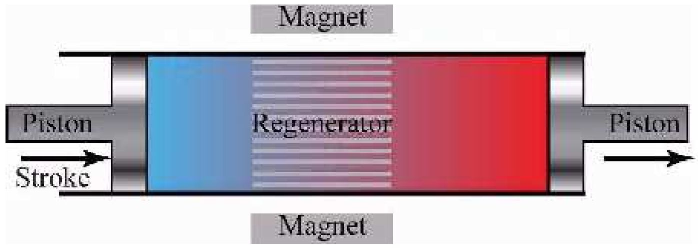


Figure 3- 4 Shows the AMR based on linear reciprocating design and Steady state temperature profile across the regenerator. [6]

1. Adiabatic magnetization: In this process, AMR moves into the magnetic field and temperature of the bed increases by ΔTad due to MCE. The regenerator heats the fluid.

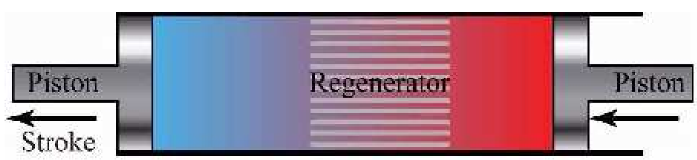


2. Cold to hot flow: The heat transfer fluid flows from cold end into the regenerator. It gains the heat from hot reservoir, so its temperature increases. Hot fluid rejects heat to the surrounding through HTEX.



3. Adiabatic demagnetization: During this process, AMR is moved out of the regenerator. So its temperature decreases by ΔTad. Heat transfer fluid is cooled due to contact with AMR.

4. Hot to cold flow: During this process, hot fluid, which is in HTEX flows through regenerator. It looses heat to regenerator and gets cooled. And enters into the CHEX from where it absorbs the heat from cooling load.



3.3.2 Rotary AMR:

In astronautics rotary magnetic refrigerator, magnetocaloric material is filled in a wheel. Magnetic field is applied by a permanent magnet having a gap. Permanent magnet covers a specified degree of over regenerator. Fluid flow is provided by a single pump. When bed is in high field region; hot fluid comes out of the bed and is transferred to HTEX and it exchange heat with ambient. The cold fluid, which comes out of bed when it is in low magnetic field, is transferred to CHEX. In CHEX, it takes the cooling load. With this arrangement, work required to enter material in high magnetic field assists to remove the bed out of magnetic field. The wheel is divided into three sectors and each sector is filled with porous magnetocaloric material. The wheel is rotated through this gap of 1.5 T magnets. When a sector is in magnetic field, radial pipes carry the cold fluid from CHEX into the middle the sector and hot fluid is removed from the end of the sector. Hot fluid is transferred to HTEX. Fluid is carried in opposite direction when sector is in low magnetic field region. For each sector we get two AMR beds due to fluid flow arrangement. These two beds are with cold ends together while hot ends are separated. Hence wheel is divided into six AMR beds. The radial pipes from hot ends of the sectors are connected to ports of rotating part of a disk valve, which is placed above the wheel. The fixed portion of the upper valve is connected to ends of the HTEX with a pump placed between. And the pipes from cold side of sector are connected to rotating part of another disk valve, which is placed below the wheel. The fixed part of lower disk valve is connected to CHEX. The ports of rotating and fixed parts of disk valve interact to correctly switch the flow with wheel rotation. Arrangement is such that pump runs continuously and flow in the heat exchangers is unidirectional. Frequency of operation is up to 4 Hz. [4]

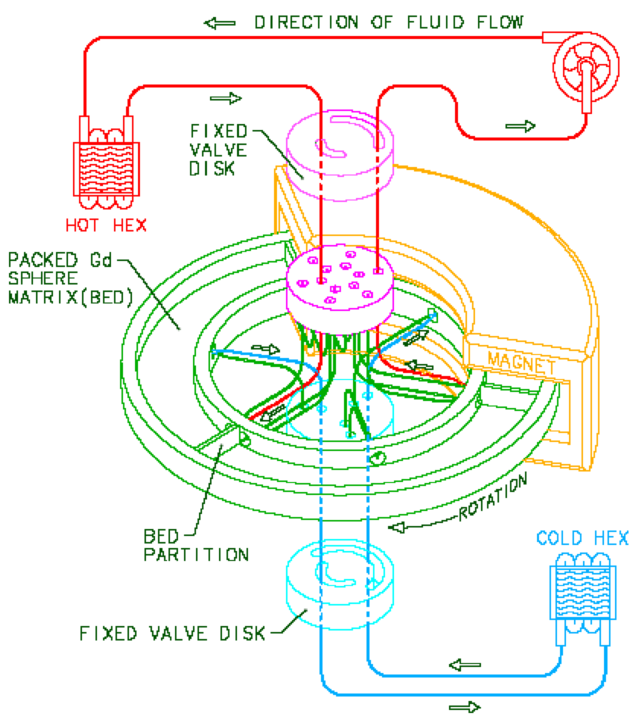


Figure 3- 5 Rotary magnetic refrigerator [4]

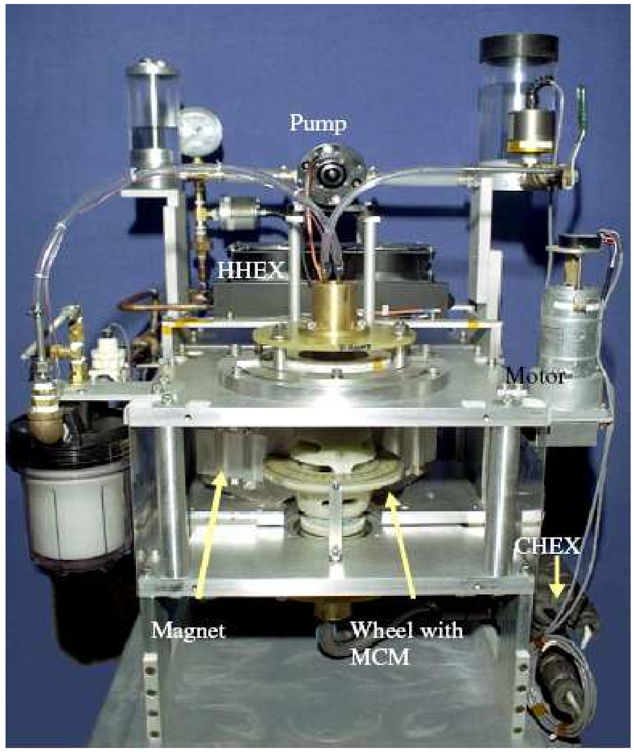


Figure 3- 6 Photograph of rotary magnetic refrigerator [4]

Chapter 4

Modeling of reciprocating active magnetic regenerator

Two-dimensional mathematical model:

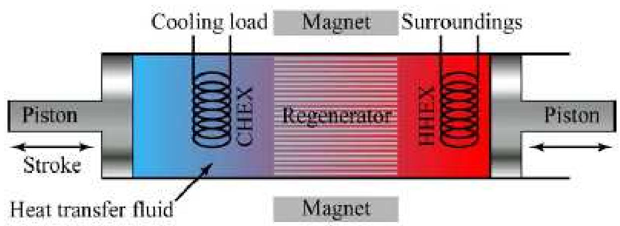


Figure 4- 1 Schematic of AMR [6]

Figure shows the geometry of the AMR considered for modeling purpose. The regenerator is made of parallel plates arranged in stack configuration. Two heat exchangers are placed at both ends of regenerator with a small gap between regenerator and heat exchangers. The gap between regenerator and heat exchangers ensure that heat transfer to and from regenerator occurs through heat transfer fluid. The heat exchangers are modeled as plates. The gap is thermally insulated and omitted from the model geometry. This assumption is reasonably well because it either contains low thermal conductivity fluid or it made of a material which is an insulator. Pistons are used for movement of heat transfer fluid. In this case, water is used. Neglecting the boundary effects, the repetitive design of regenerator allows the full geometry to be reduced to a repeating unit. [5]

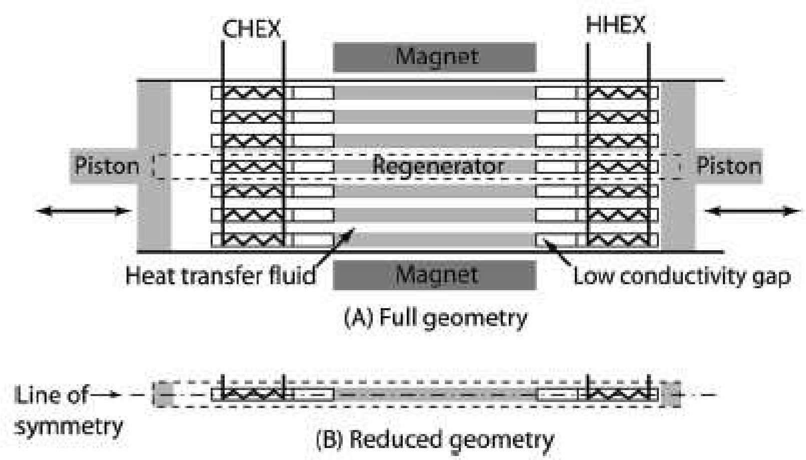


Figure 4- 2(a) Shows the full geometry with parallel plate type regenerator and heat exchangers placed at ends, (b) repeating with a single regenerator plate with fluid flows from either side [5]

Governing equations of model: [5]

Velocity distribution in the fluid is calculated by solving continuity and momentum equation for incompressible fluid. The other properties are kept constant. These equations are solved without knowing temperature distribution.

$\nabla.U = 0$ ……………………………………………………………… (1)

$\rho_f((\partial U/\partial t) + (U.\nabla)U) - \nabla^2 U + \nabla p = 0$ ……………………………… (2)

ρ_f = density of the fluid

μ_f = dynamic viscosity of the fluid

U = 2-D velocity field (u, v)

P = pressure

To determine the temperature distribution in the AMR, coupled heat transfer equations are solved for solid domain and fluid. Solid domain consists of regenerator and heat exchangers. The temperature distribution for solid domain is determined by following heat transfer equation.

$\rho_S C_{P,S}(\partial T_S / \partial t) + \nabla.(-K_S \nabla T_S) = 0$ ……………………………………. (3)

Where, ρ_S is density of solid domain, C_{ps} is heat capacity, K_S is thermal conductivity and Ts is the surface temperature. The temperature distribution in the fluid is determined by the heat transfer equation for incompressible fluid with convective terms.

$\rho_F C_{P,F}((\partial T_F / \partial t) + (U.\nabla)T_F) + \nabla.(-K_F \nabla T_F) = 0$ ………………………… (4)

Where, ρ_F is the density of fluid, μ_F is the dynamic viscosity of fluid, T_F is temperature of the fluid and K_f is the thermal conductivity of the fluid. The velocity distribution is used to determine convective heat transfer. Heat capacity is temperature dependent, which is evaluated at T_H.

It is assumed that the magnetization and demagnetization occurs instantaneously. So it is adiabatic and modeled as temperature change by ΔTad.

$$T = Ti + \Delta T_{ad}(Ti, \mu_0 H_0) \quad \text{……………………………………………………….. (5)}$$

Where, T is local temperature of regenerator bed and Ti is initial temperature of regenerator. And μ_0 is permeability of vacuum.

Boundary conditions:

The following boundary condition is to relate solid and fluid assuming both are in perfect thermal contact.

$$K_F(\partial T_F / \partial Y) = K_S(\partial T_S / \partial Y) \quad \text{……………………………………………………… (6)}$$

The boundary condition for the CHEX is given by following equation

$$q''_c = h_C(T_C - T\ ) \quad \text{………………………………………………………………… (7)}$$

q''_c is the cooling load per unit area, h_C heat transfer coefficient of CHEX and T_C is the temp of CHEX.

The boundary condition for HTEX is given by

$$q''_r = h_H(T - T_H) \quad \text{………………………………………………………………… (8)}$$

q''_r is the rate of heat rejection per unit area, h_H is the heat transfer coefficient of HTEX and T_H is temperature of HTEX.

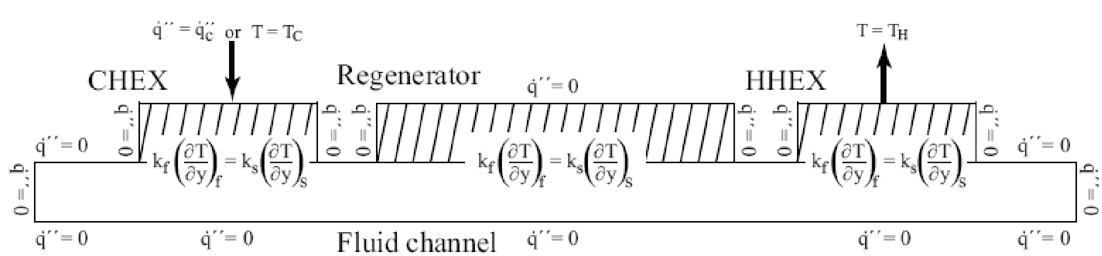


Figure 4- 3 shows the overall boundary condition for AMR model [5]

Evaluation of AMR performance:

COP of the cycle is determined by following equation

COP= q'_C / W' …………………………………………………………………. (9)

q'_C is the amount of heat absorbed in the CHEX per unit width and W' is amount of work supplied per unit width

The amount of heat absorbed per unit width of the CHEX per cycle is determined by following equation

$$q'_C = \int_0^\tau \int_O^L q''_C \, dxdt \quad \text{(10)}$$

τ is the cycle period and L is the length of heat exchanger

The heat rejected per unit width of HTEX per cycle is calculated by

$$q'_r = \int_0^\tau \int_O^L q''_r \, dxdt \quad \text{(11)}$$

The work required in magnetization and demagnetization process is calculated from the first law of thermodynamics.

$$W' = q'_r - q'_C \quad \text{(12)}$$

Table 1 Geometrical dimensions used in the model [5]

Part	Material	Length (cm)	Height (mm)
Regenerator	Gadolinium	5	0.5
Heat exchangers	Copper	2	0.5
Fluid	Water	16	0.5
Gap between heat exchangers and regenerator	–	1	0.5

Table 2 Process parameters of AMR cycle [5]

Parameter	Value and unit
Piston stroke	2 cm
Cycle period (τ)	6 s
τ_1 and τ_3	2 s
τ_2 and τ_4	1 s
$\mu_0 H$	1 T
T_H and initial temperature	298 K
h_H	10^6 W m^{-2} K^{-1}
h_C	0 W m^{-2} K^{-1}

Results:

The AMR model is implemented with system geometry as shown in table 1. Gd is used as regenerator material. The process parameters used are shown in table no. 2. Perfect thermal contact between HHEX and surrounding is used as first assumption and obtained high value of heat transfer coefficient at HHEX. The CHEX is thermally insulated. The heat transfer coefficient at CHEX is set to zero. So that all work applied is rejected from HHEX. After 600 cycles steady state is achieved. The adiabatic temperature change is 10.9 K. the total work input per cycle is 4.65 j/m per regenerator plate corresponding to 93.0 KJ/m^{-3} of Gd. Since piston work is very less so it is neglected. [5]

Conclusion

The maximum magnetocaloric effect depends on Curie temperature. If we deviate from Curie temperature, there is large reduction in adiabatic temperature change. Those materials undergo order-disorder phase transition; the maximum adiabatic temperature change is very small in small magnetic field supplied by permanent magnet used for room temperature refrigeration. But those material undergo first order phase transition, the adiabatic temperature change is very large in small magnetic field as compared to order-disorder phase transition materials. Astronautics Corporation of America constructed a rotary type active magnetic regenerator refrigerator, which uses 1.5 T magnetic fields. This refrigerator works reliably over a range of frequencies up to 4 Hz. Two dimensional mathematical models predict the temperature profile through the regenerator and evaluate the temperature span and input work of AMR.

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