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Simulation of Magnetic Field Distribution in the Rotary Regenerator Bed of Active Magnetic Refrigerator (AMR) using Finite Element Analysis (FEA)

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Abstract—

The Magneto Caloric Effect is an intrinsic property of a magnetic solid. It is the response of this solid to the application or removal of magnetic fields. When magnetic material (Regenerator) is subjected to a magnetic field the magnetic moments are aligned and the magnetic entropy is lower. And the sample heats up when the field is removed the magnetic entropy is increased and the temperature is lowered. The magnitude of the magnetic entropy and the adiabatic temperature changes are strongly dependent upon the magnetic order process. The objective of this work is to investigate the effect of magnetic field on the regenerator bed. The entropy depends not only on temperature but also on some other quantity, in this case magnetic field. Therefore, these materials can be forced to undergo various types of thermodynamic cycles that cause entropy to move from a low temperature to a high temperature due to a work input. A Finite Element model is built and meshed in ANSYS 10.0 Emag Module. Thermal analysis is done on the magnetic material using commercial FEA software ANSYS 10.0. Magnetic field distributions can be estimated using ANSYS Electromagnetic analysis.

Key Words: Magnetic Field Distribution, Magnetic Refrigeration, Finite Element Analysis

I. INTRODUCTION

Investigation of magneto thermal phenomenon in magnetic materials is of great importance for solving fundamental problems of magnetism and solid state physics, as well as for technological applications [3]. This phenomenon have a strong influence on physical values such as entropy, heat capacity and thermal conductivity and reflects by themselves, transformations taking place in spin structure of a magnetic material [4]. The present work mainly devoted to the finite element results on the Magneto Caloric Effect (MCE). Magnetic Analysis is of great importance in proper distribution configurations of flux densities in the rotary regenerator.

II. ANALYSIS

A porous, packed bed of magnetic material is exposed to a time-varying magnetic field [5]. In this system, a mass of magnetic material is rotated sequentially through a cold thermal reservoir, an adiabatic magnetic field, a warm thermal reservoir, and an adiabatic region with no magnetic field (Fig 1). The process undergone by the magnetic material approaches the Carnot cycle [6-13].

III. ANALYSIS PROCEDURE IN ANSYS

PLANE13 element is considered for analysis in ANSYS 10.0. PLANE13 has a 2-D magnetic, thermal, electrical, piezoelectric and structural field capability with limited coupling between the fields. The element has nonlinear magnetic capability for modeling B-H curves or permanent magnet demagnetization curves. 2-D model is built in ANSYS 10.0 as shown in figure 3.1. The model is meshed with triangular elements.

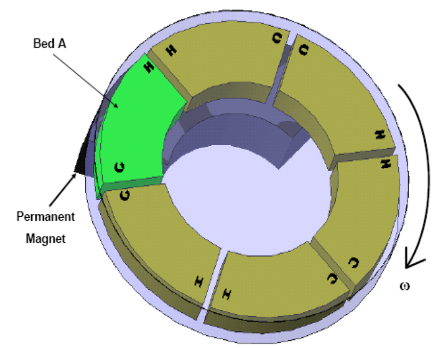

Fig 1 Schematic Diagram of Rotary Regenerator

IV. BOUNDARY CONDITIONS

The Boundary conditions for the model are, a magnetic field strength of 4T is applied to the magnetic refrigerant Gd. PLANE 13, 2-D quadrilateral coupled field solid is chosen as element type. PLANE 13 is having 4 node capabilities with four degrees of freedom for each node as constraint.

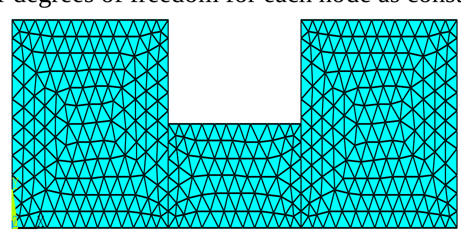

Fig 2 Meshed model of the regenerator

The element (Fig 2) has also non-linear capabilities to suit the changes in B-H curve. The permeability of free space is

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considered to be 4π x10^{-7} H/m. And the relative permeability is considered to be 5000 [14].

V. GOVERNING EQUATIONS

The heat capacity increases with respect to large entropy gradients according to the definition [15],

$$C_P = T\left(\frac{\partial S}{\partial T}\right)_P \qquad (1)$$

where C_P is the specific heat capacity at constant pressure, T is the temperature, and S is the entropy.
The first law of thermodynamics is usually given as

$$dU = TdS - pdV \quad (2)$$

where U is the internal energy. This can be adapted for magnetic systems by replacing the -pdV term with a magnetic work term given by B_0dM [16], where M is the magnetization and B_0 is the field, giving

$$dU = TdS + B_0 dM \qquad (3)$$

By comparing (2) with (3), it is clear that to generate thermodynamic equations for a magnetic system; P must be replaced with $-B_0$ and V with M. This retains the usual pairing of intrinsic and extrinsic variables found in the equations. The other three thermodynamic potentials, the enthalpy H, the Helmholtz free energy F, and the Gibbs free energy G follow from the internal energy,

$$dH = TdS - MdB_0 \qquad (4)$$

$$dF = B_0 dM - SdT \qquad (5)$$

and

$$dG = -MdB_0 - SdT \qquad (6)$$

The four Maxwell relations can be generated from the thermodynamic potentials, using the fact that U, H, F, and G are exact differentials.
Equation (6) gives

$$\left(\frac{\partial T}{\partial M}\right)_S = \left(\frac{\partial B_0}{\partial S}\right)_M \qquad (7)$$

(7) gives

$$\left(\frac{\partial T}{\partial B_0}\right)_S = -\left(\frac{\partial M}{\partial S}\right)_{B_0} \qquad (8)$$

(8) gives

$$\left(\frac{\partial B_0}{\partial T}\right)_M = -\left(\frac{\partial S}{\partial M}\right)_T \qquad (9)$$

and (9) gives

$$\left(\frac{\partial M}{\partial T}\right)_{B_0} = \left(\frac{\partial S}{\partial B_0}\right)_T \qquad (10)$$

The quantity needed in order to predict the performance of magnetic refrigerator is the change in temperature produced by a change in magnetic field at constant entropy, the left-hand side of equation(10). Using the chain rule, the right hand side can be rearranged to give

$$\left(\frac{\partial T}{\partial B_0}\right)_S = -\left(\frac{\partial M}{\partial T}\right)_{B_0}\left(\frac{\partial T}{\partial S}\right)_{B_0} \quad (11)$$

The definition of the specific heat capacity at constant magnetic field is

$$C_{B_0} = T\left(\frac{\partial S}{\partial T}\right)_{B_0} \qquad (12)$$

Substituting this into equation (11) gives

$$\left(\frac{\partial T}{\partial B_0}\right)_S = -\frac{T}{C_{B_0}}\left(\frac{\partial M}{\partial T}\right)_{B_0} \quad (13)$$

which is known as the Langevin [17] expression for the temperature change produced by adiabatic demagnetization.

VI. RESULTS & DISCUSSION

A well-designed magnetic system may be competitive with or even more efficient than vapor compression systems. Figures 3 and 4 shows that no flux leakage occurs thorough the regenerator as flux lines never crossed the boundary. And it is the resultant of field strength in X - direction and Y- direction as shown in figures 5 and 6. Figure 7 show that magnetic field strength is maximum in the centre layers of regenerator material. This results in choosing of the thin layered beds for regenerator.

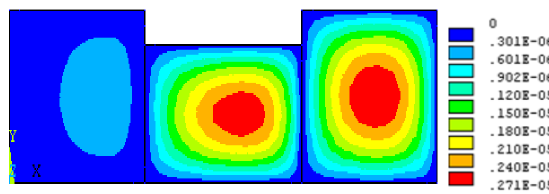

Fig 3 2-D Electromagnetic Analysis DOF Solution

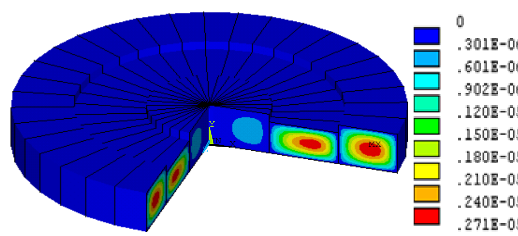

Fig 4 3-D Electromagnetic Analysis DOF Solution

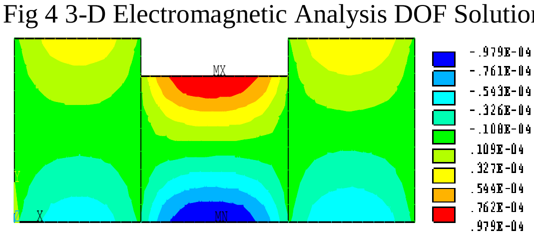

Fig 5 2- D Contours of Magnetic Field Strength in X-Direction

The thinner the layer the more is the magnetic field strength in the regenerator. Magnetization of the regenerator material has also shown similar trend as shown in figures 8, 9 and 10.

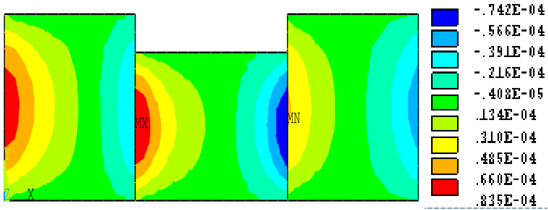

Fig 6 2- D Contours of Magnetic Field Strength in Y- Direction

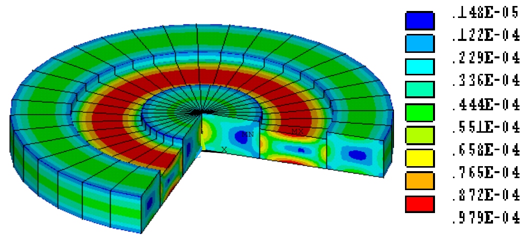

Fig 7 3- D Contours of Magnetic Field Strength

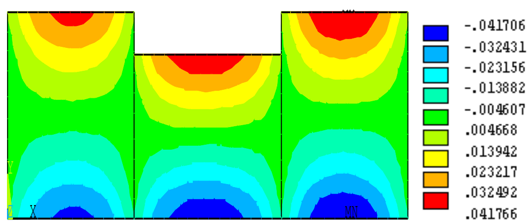

Fig 8 2- D Contours of Magnetization in X- Direction

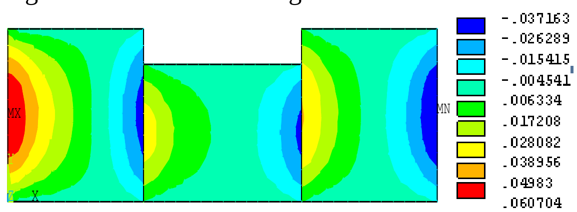

Fig 9 2- D Contours of Magnetization in Y- Direction

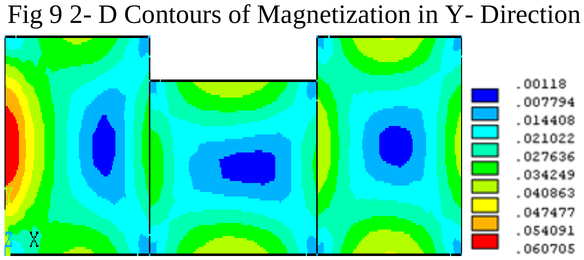

Fig 10 2- D Contours of Magnetization

Electromagnetic analysis revealed that no leakage of the magnetic flux occurs in the regenerator. Leakage of the flux indicates the magnetization capability on the regenerator bed. The lesser the leakage the more is the magnetization capability. And hence more is the entropy change. The maximum entropy (magnetic) change can cause maximum cooling effect.

VII. Conclusions

The estimation of magnetic field distribution in the rotary bed regenerator of Active Magnetic Refrigerator reveals that the lower and upper layers of bed are at lower fields in the regenerator. Field non uniformity is observed in the layers of regenerator bed. The coefficient of performance of overall refrigerator can be enhanced with the uniform magnetic field due to magnetization of the regenerator bed.

Acknowledgments

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