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Finite Element Analysis (FEA) on Rotary Regenerator Bed of Active Magnetic Refrigerator (AMR): Temperature Distribution

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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 [1]. When magnetic material 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 [2]. The objective of this work is to investigate the effect of temperature 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. Thermal analysis is done on the magnetic material using commercial FEA software ANSYS 10.0. Temperature distributions can be estimated using ANSYS thermal analysis.

Key Words: Temperature 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). Thermal Analysis is of great importance in proper distribution configurations of thermal fluxes 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].

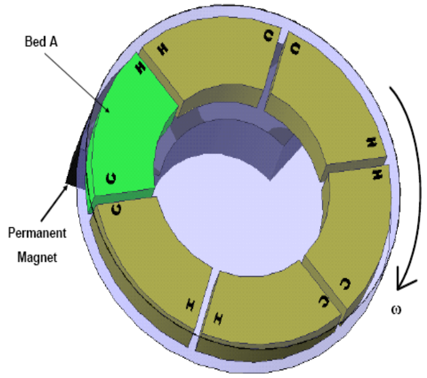

Fig 1 Schematic Diagram of Rotary Regenerator

A Finite Element model is built and meshed in ANSYS 10.0. Thermal analysis is done on the magnetic material using commercial FEA software ANSYS 10.0. Temperature distributions can be estimated using ANSYS thermal analysis.

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 2. The model is meshed with triangular elements.

IV. BOUNDARY CONDITIONS

The Boundary conditions for the model are, a magnetic field strength of 2T is applied to the magnetic refrigerant Gd. Plane13, 2-D quadrilateral coupled field solid is chosen as element type. The permeability of free space is considered to be $4\pi \times 10^{-7}$ H/m. And the relative permeability is considered to be 5000 [14].

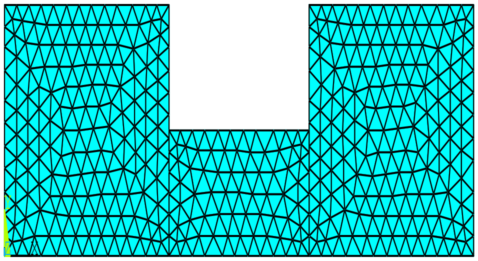

Fig 2 Meshed model of the regenerator

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. Thermal analysis on regenerator shows that the temperature that can be reached by the regenerator (Gd) is 10K. Figures 3 and 4 show that the temperature of the regenerator is minimum at the lower layers of the bed. Thermal gradients are shown in figures 5, 6 and 7 and corresponding 3-D models are shown in Figures 8, 9 and 10 respectively are minimum within the regenerator which will enhance the heat transfer from the cooling medium to the regenerator. This is the indication of the losses in the regenerator which are observed to be minimized. More thermal gradients within the regenerator may cause more temperature drop within the regenerator. And that may cause losses in the heat transfer from cooling medium to the regenerator. The product of temperature and the partial derivative of the fluid heat capacity with temperature is assumed to be much less than the specific heat capacity itself; therefore, the terms in the energy equation associated with the fluid flow and fluid energy storage are related only to the local specific heat capacity.

The thermal capacity of the fluid entrained in the matrix is lumped together with the thermal capacity of the matrix itself; this implies that the time derivatives of the fluid and regenerator temperatures are of similar magnitude which is a good assumption provided that the local temperature difference between the fluid and regenerator is small in comparison with the overall temperature range spanned by the regenerator; note that this assumption is at least approximately relaxed by correcting for the entrained fluid capacity.

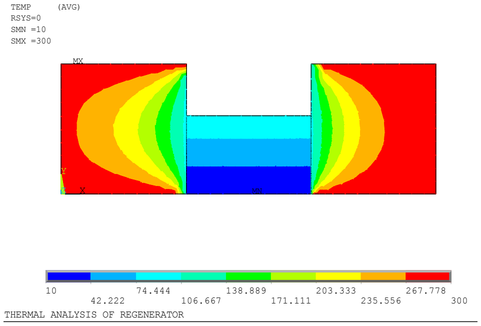

Fig 3. 2-D DOF (Temperature) Solution

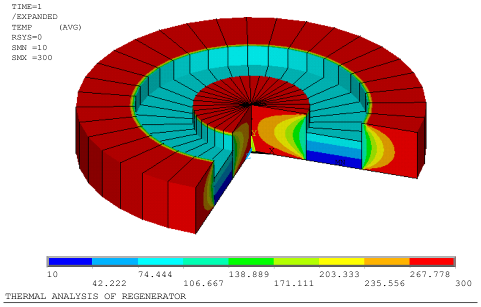

Fig 4. 3-D DOF (Temperature) Solution

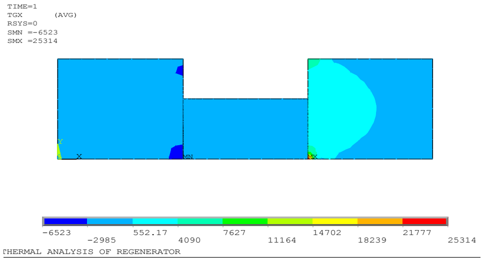

Fig 5 2-D Contours of Thermal Gradient in X- Direction

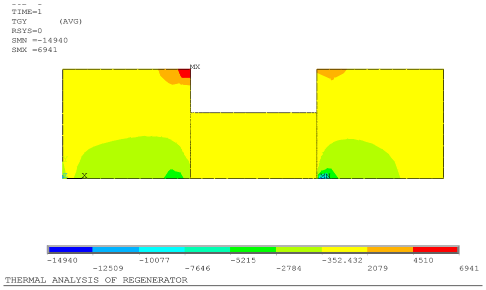

Fig 6 2-D Contours of Thermal Gradient in Y- Direction

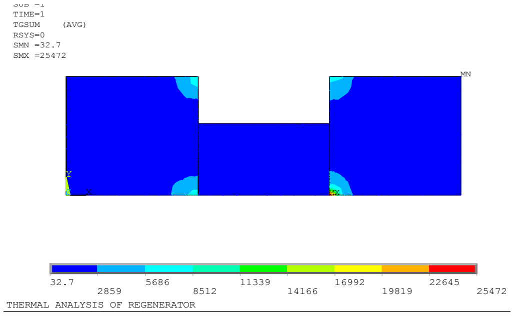

Fig 7 2-D Contours of thermal Gradient

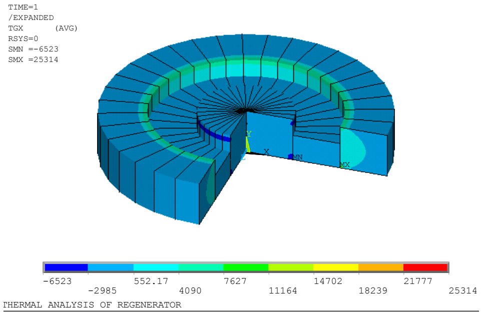

Fig 8. 3-D Contours of Thermal Gradient in X- Direction

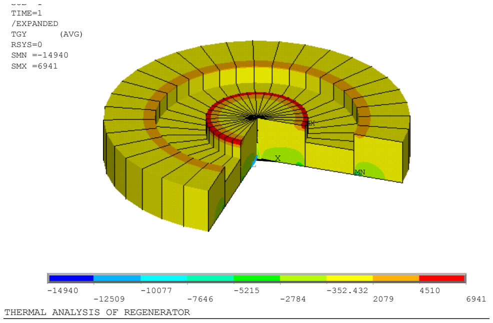

Fig 9. 3 D Contours of Thermal Gradient in Y- Direction

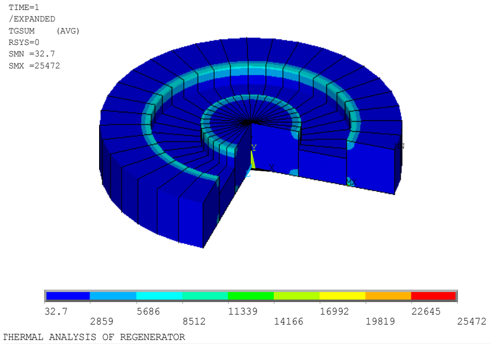

Fig 10. 3-D Contours of thermal Gradient

VII. CONCLUSIONS

The estimation of temperature distribution in the rotary bed regenerator of Active Magnetic Refrigerator reveals that the lower layers of bed are at lower temperature as compared to the upper layers of regenerator. Heat transfer from the regenerator bed can be increase with higher thermal gradients which are also observed near the lower layers of regenerator bed. The coefficient of performance of overall refrigerator can be enhanced with the selected regenerator and with frequency of rotation of the bed through the magnetic field.

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