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PERFORMANCE-ORIENTED ANALYSIS OF A HYBRID MAGNETIC ASSEMBLY FOR A HEAT-PUMP MAGNETOCALORIC DEVICE

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ABSTRACT — Conventional active-regenerator magnetocaloric devices include moving parts, with the purpose of generating an oscillating magnetic field in the magneto-caloric material, placed inside the regenerator. In this work a different design is analyzed, for application in a magnetocaloric heat pump. In this design all the parts of the machine are static and the oscillating field is generated by varying the currents of electromagnets included in the hybrid magnetic assembly. The use of different permanent magnet materials is compared with the perspective of maximizing the coefficient of performance of the device.

1. INTRODUCTION

The magnetic assemblies designed for magnetocaloric refrigeration are necessarily realized without using electromagnets, since the heat produced by the Joule effect would decrease the overall performance of the device. In order to work, any magnetocaloric device must produce a time oscillating magnetic field inside the magnetocaloric material. When the magnetic assembly is realized without the use of electromagnets, there are two main options[1] to produce the field oscillation inside the material: rearrange different parts of the magnetic assembly to modify the field, or displace the material itself in different positions characterized by different values of magnetic field. Both the options have some disadvantages: additional design challenges are introduced, the lifespan of some components of the machine is reduced because of friction and vibrations associated with the motion. A magnetocaloric heat pump does not share this limitation with the refrigerators and the use of a hybrid magnetic assembly, which includes also electromagnets, is feasible. The Joule dissipation in the coils of the electromagnets will generate an additional heating output. Moreover a new option is available to produce the oscillating field inside the magnetocaloric material: the coil-current of the electromagnets can be varied to alter the magnetic field while all the parts of the device are stationary. This design solution is not affected by the disadvantages of moving machines, and would also result in a minor noise production. One prototypical geometry for a static machine with hybrid magnetic assembly will be analysed, with the perspective of maximizing the net performance of the magnetocaloric heat pump.

2. METHODS

We will consider one prototypical geometry for static machines with hybrid magnetic assembly and describe the methods we employed to model this system. The geometry is schematically illustrated in Fig. 1 and consists in a high-permeability material (iron) core composed by two loops (left and right loop).

A permanent magnet magnetized in the vertical direction is placed in the central branch of the circuit. Two air gaps, which will host the magnetocaloric regenerators, are located in the middle of the left and right branches. Finally, two electric coils are wrapped around the left and right branches of the circuit (in the figure the coils are placed right around the air gaps, but any position would be equivalent as long as each coil is interlocked with the respective iron-core loop).

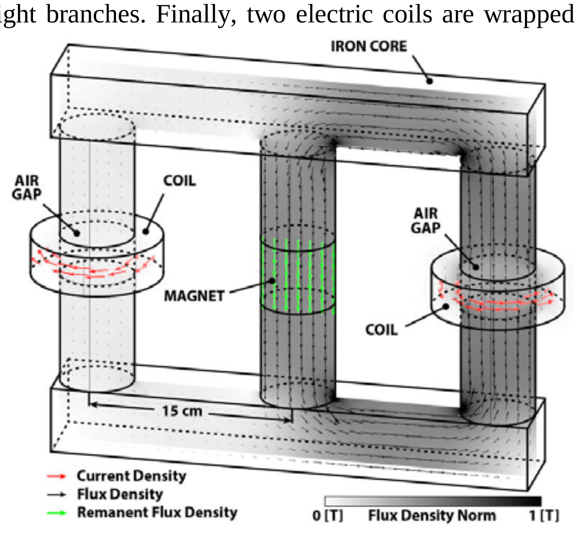

Fig. 1. Schematic illustration of the double-loop geometry. The right air gap is in the high-field state.

The geometry is modelled as a magnetic circuit composed by its different elements connected through common nodes. Each element is characterized by uniform magnetic field, *H*, and flux density, *B*, and by a couple of geometric parameters: length and cross-section area. In analogy with an electric-circuit, the system is governed by a conservation equation for each node and one for each loop. Gauss's law for magnetism implies the conservation of the magnetic flux at each node. Ampere's law implies that the line integral of *H* over each loop is equal to the electrical current flowing through the loop. The final ingredient to complete the model is a constitutive *B*-*H* relation for each material. This means that there is no flux leakage from the air gaps. In this analysis the following materials will be considered: air, iron, neodymium-iron-boron (NdFeB) magnet and aluminium-nickel-cobalt (AlNiCo) magnet. The demagnetization branch of the *B*-*H* curve of each of the relevant materials (except air) is plotted in the left panel of Fig. 2. We developed a model in Matlab that interpolates the constitutive relations from a set of (*B*,*H*) points passed as input, and then numerically solves the resulting magnetic-circuit equations. The program returns as outputs the values of the flux density inside each air gap. The results given by this simplified model are less realistic than what could be obtained with a finite element analysis of the geometry, but the computational cost is much lower, making it a suitable tool for a preliminary analysis.

The operation of the device (i.e. the time dependence of the coil-currents) is determined by the characteristics of the thermo-dynamical cycle of the magnetocaloric material. The focus of this work will be on cycles for which the materials spend half of the cycle time in high-field state and the other half in a low-field state. In this device the coils augment the field in one of the air gaps while simultaneously reducing it in the other for one half of the cycle. During the other half of the cycle the high-field and low-field air gaps are switched. The current is parameterized by the high-field state current value, I_H, and the low-field state value, I_L. In every moment of the cycle both these currents are occurring simultaneously on the two coils. Instead of using these parameters, however, the following expressions are used: $I_H = I \cos\phi$, $I_L = I \sin\phi$. In this way the net power, α, spent by the machine by Joule dissipation, is not dependent on the 'current-angle' ϕ, but only on the square I^2 of the 'current-amplitude', that is equal to the sum of the squares of the two components. The performance of the device is expressed by the Coefficient Of Performance, COP, which is defined[2] as the ratio between the output heating power and the input power: COP $=(Q_C + P_0 + \alpha)/(P_0 + \alpha)$, where P_0 is the net 'base' power (i.e. the power spent by the machine in other parts than the electric coils, for example the pump of the heat-exchange fluid), and Q_C is the cooling power generated by the magnetocaloric effect. It is assumed[3] that the cooling power is given by $Q_C = \gamma\, \Lambda_B = \gamma\, (B_H^{2/3} - B_L^{2/3})$, where γ is the cooling factor and B_H and B_L are respectively the high and low values of the norm of the flux density.

3. Results

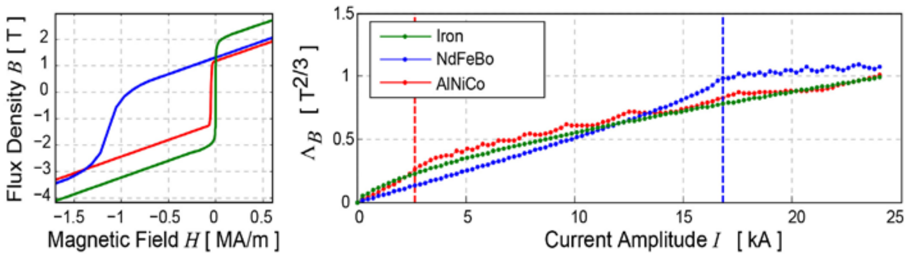

Fig. 2. Left panel: Demagnetization branch of the *B-H* curves of the relevant materials. Right panel: value of Λ_B as a function of I, for the optimal choice of ϕ.

The analysis based on this model can be used to optimize different geometrical and operational parameters of the heat-pump device. The starting point is to determine the optimal value of ϕ for each value of I and each permanent magnet material. This result is shown in the right panel of Fig. 2. The value of Λ_B (vertical axis) is plotted as a function of I (horizontal axis) for the different materials corresponding to the *B-H* curves plotted in the left panel. The plotted $\Lambda_B(I)$ curves correspond to the optimal choice of ϕ for a given value of I. The vertical dashed lines correspond to the minimum value of I necessary to completely cancel the field B_L for each material. The plot indicates that for very low values of I the best performance would be obtained by replacing the permanent magnet material with iron. For higher current values, (approximately between the red dashed line and the blue dashed line), AlNiCo would be the better-performing material. For even higher current values the best choice would be NdFeB, but the value of Λ_B remains of the same order of magnitude of the other materials. These results are consequences of the 2/3 exponents weighting the fields, B, in the expression of Λ_B. Because of these exponents, it is more convenient to reduce B_L than it is to increase B_H. For values of I large enough to cancel B_L, the optimal ϕ is determined by the condition that the flux density in the low field region is not reversed (thus increasing its norm). For this reason AlNiCo, or even iron, could perform better than NdFeB for some values of I.

4. Conclusions

This analysis has been used to determine, for arbitrary values of base power P_0 and cooling factor γ, the optimal values of ϕ and I, and the better-performing material. The optimality parameter is the coefficient of performance COP of the final heat-pump device, which, once the values of P_0 and γ are known, can be predicted by this model. Within this framework it is possible to compare the performance of this geometry or similar static devices, with the performance of more conventional designs with moving parts.
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