Multi-physics analysis of a magnetocaloric cooling system

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***Abstract*— This paper presents a weak coupling methodology between a 3D FEM magnetostatic model, an analytic magnetocaloric model and a thermal model solved with finite difference method. This methodology has been applied to analyze a magnetocaloric cooling system taking into account 3D effects in magnetic field computation.**

***Index Terms*—Magnetic refrigeration, Magnetocaloric effect, Numerical models.**

I. Introduction

The reduction of energy consumption represents one solution to decrease the emission of greenhouse gases. As the refrigeration technologies consume more than 15% of worldwide consumption of electricity [1], the design of efficient refrigeration systems is a key point for successful applications. The magnetocaloric cooling systems represent a promising alternative to classical refrigeration systems since the magnetic field is directly used to perform the heat pumping. Thus, an accurate modeling of magnetocaloric systems, considering its multi-physical behavior, is essential to obtain more realistic simulations of their real working.

Several analytical models have been proposed to take into account the thermo-magnetic properties together with the thermo-fluidic phenomena [2-3]. In order to be to consider more complex geometries, the modeling of 3D effects in magnetic field computation using FEM magnetostatic model can be advantageous. Then, this paper proposes a consistent coupling procedure between magnetostatic equations solved with Flux3D® code [4], an analytic magnetocaloric model and a thermal model solved with finite difference method, to simulate the thermo-magnetic behavior of a magnetocaloric cooling system.

II. Magnetostatic model

The magnetostatic model requires the value of the electrical current in the windings and *B*(*H*) characteristic of the magnetocaloric material (gadolinium). As shown in Fig. 1, the gadolinium shows particular properties depending on its temperature along with external magnetic field and exhibits a ferromagnetic behavior for temperatures below 293 K, becoming paramagnetic above 293 K (critical transition).

Therefore, before each magnetic resolution, an interpolation has to be done according to the temperature of the material, in order to determine the *B*(*H*) curve of the material, the magnetostatic equations being solved with a 3D finite element software (Flux3D®) [4]. The outputs of this model [5] are the different values of magnetic field in the gadolinium.

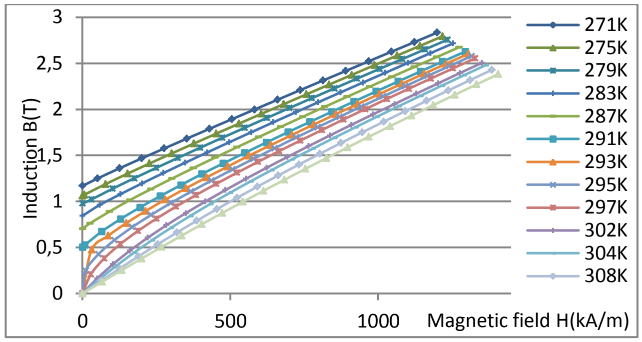

Fig. 1. *B*(*H*) characteristics of the gadolinium as function of temperature

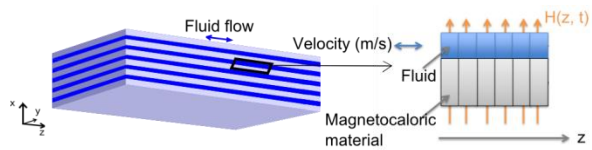

Fig. 2. 1D model for the thermal model

III. Magnetocaloric and thermal models

A. *Magnetocaloric model:*

The thermal power density produced by the interaction of the gadolinium material according to the magnetic field variation is calculated with (1) [6]:

$$\dot{q} = -\mu_0 \cdot T \cdot \left(\frac{\partial M}{\partial T}\right)_H \cdot \frac{dH}{dt} \qquad [\mathrm{W/m^3}] \qquad (1)$$

where *T*, *M* and *H* are the temperature, magnetization and local magnetic field intensity respectively.

This model requires the output of the magnetostatic model. So, using the actual local values of magnetic field and temperature, and taking into account the demagnetizing field, we can determine the magnetization and the gradient of magnetic field, and then calculate the local magnetocaloric power production.

B. *Thermal model*

The thermal model is based on a 1D model in the fluid flow direction *z* (Fig. 2). The following equations describe the thermal behavior of a fluid element (subscripts: f) and a magnetocaloric material element (subscripts: m) [7].

$$\begin{cases} m_f \cdot C_f \cdot \left(\dfrac{\partial T_f}{\partial t} + V(t) \cdot \dfrac{\partial T_f}{\partial z}\right) = h(t) \cdot S \cdot (T_m - T_f) \\ m_m \cdot C_p(H, T_m) \cdot \dfrac{\partial T_m}{\partial t} - \lambda \cdot v \cdot \dfrac{\partial^2 T_m}{\partial z^2} = \dot{q} \cdot v + h(t) \cdot S \cdot (T_f - T_m) \end{cases} \qquad (2)$$

where *T*, *h*, *S*, λ, *v*, *q*, *m*, *C*, *V* are the temperature, convection coefficient, exchange surface, thermal conductivity, solid cell volume, magnetocaloric power density, mass, specific heat capacity and velocity of the fluid respectively. To solve these coupled equations, the finite difference method with explicit scheme has been used and coded with Python; the Courant-Friedrich-Levy criterion ($V \cdot \frac{\Delta T}{\Delta z} < 1$ where $\Delta T, \Delta z$ are the time step and the spatial discretization respectively) [8] is tested to ensure the convergence of the model. The ambient temperature is the initial condition, and the hot and cold tank temperatures are the limit conditions.

IV. COUPLING MODELS AND FIRST RESULTS

The coupling of the three models is coded in a single program with Python 2.7.2. The coupling strategy is the following (Fig. 3):

1. According to the time and the temperature, the magnetocaloric material $B(H)$ curve is interpolated and then defined in Flux3D software, which is driven by Python code to solve magnetic equations.
2. According to the obtained internal magnetic field, the magnetization is deduced and the local production of heat is calculated.
3. Then, the temperatures are computed according to the heat diffusion in the material and the fluid, and these temperatures are returned to the first step and the time is incremented.

A fundamental experimental magnetocaloric cooling system has been considered to test our model. In this system, the magnetic field is produced by an electromagnet, which has been specifically designed in our laboratory (Fig. 4).

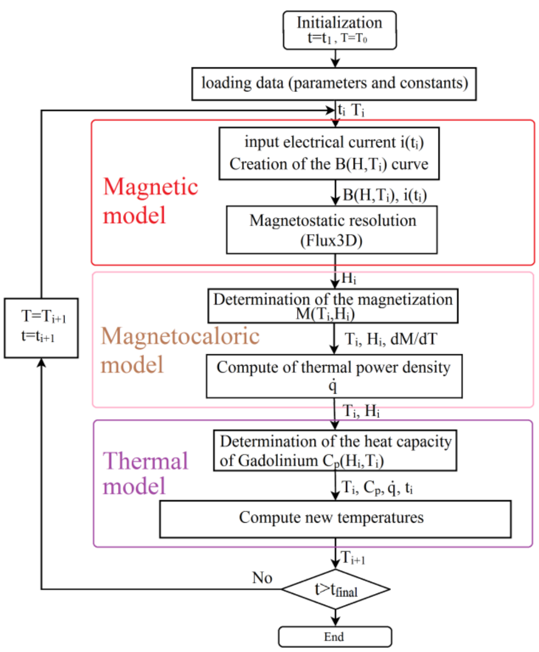

Fig. 3. Resolution algorithm of the model

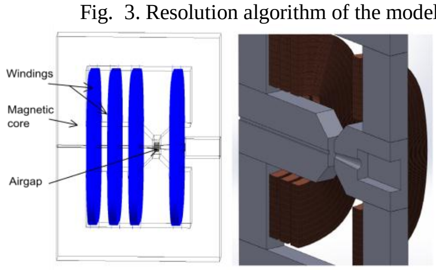

Fig. 4. 3D model of a special electromagnet

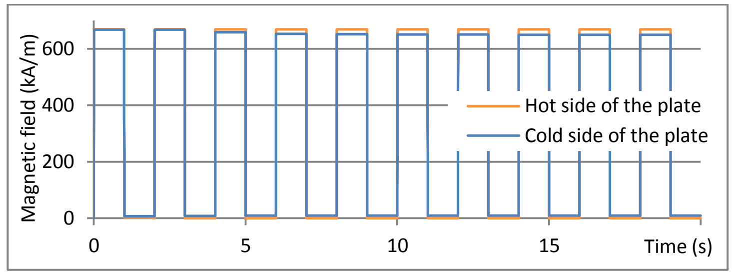

Fig. 5. Magnetic field in the gadolinium over time

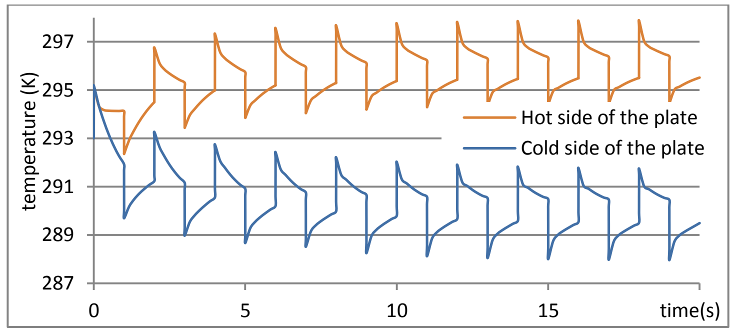

Fig. 6. Time evolution of the hot and cold sinks temperatures

The gadolinium plates ($1x13x45mm^3$) are placed in the air gap of the electromagnet and the thermal fluid (Zitrec-S10) flows between the plates in order to exchange heat alternatively with the hot and cold exchangers or sinks.

Fig. 5 shows the obtained magnetic field and Fig 6 shows the evolution of hot and cold sinks temperatures (10 thermodynamics cycles are simulated), illustrating the working of the coupled models.

V. CONCLUSION

In this paper a new multi-physics model has been proposed, based on magnetic, magnetocaloric and thermal phenomena in a magnetic refrigeration system. This model will be validated by the data obtained from an experimental test bench and, further, be used to optimize the thermal power produced by an industrial magnetocaloric system.

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