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PRODUCTION OF ARTIFICIAL COLD FOR INDUSTRY, BASED ON THE MAGNETOCALORIC EFFECT

PROIZVODNJA UMETNEGA HLADU, OSNOVANA NA MAGNETNOKALORIČNEM UČINKU

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Abstract

The most common current technology for producing artificial cold is based on the operation of gas compression and absorption, which was discovered more than a century ago. This technology uses refrigerants as a heat transfer agent. Magnetic refrigeration is an innovative technology that works based on the magnetocaloric effect and the properties of certain rare materials/metals. The present paper describes a simulation of the magnetocaloric effect (MCE) of a gadolinium plate (Gd.), which is the main component of the active magnetic regenerator (AMR). The first part includes a description and history of the discovery of the magnetocaloric effect of materials that possess such properties. The continuation is a COMSOL Multiphysics modelling of AMR's main component: a gadolinium (Gd) plate. The simulation of the magnetocaloric effects and the heat dispersion on its surface was done in COMSOL, as was the highlighting of the adiabatic temperature on the flat surface of the plate. Water

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was used as a heat transfer agent, and gadolinium (Gd) was used as a reference criterion for the materials. The model simulates a single step of the magnetic refrigeration cycle and evaluates the AMR's performance with a single board. This study enables identifying the most important characteristics that influence the active magnetic regenerator's thermal behaviour.

Povzetek

Najpogostejša tehnologija za ustvarjanje umetnega hladu temelji na termodinamiki kompresorskih hladilnih strojev, ki so bili odkriti pred več kot stoletjem. Ta tehnologija uporablja hladilno sredstvo kot sredstvo za prenos toplote. Magnetno hlajenje je inovativna tehnologija, ki deluje na osnovi magnetokaloričnega učinka in lastnosti nekaterih redkih materialov/kovin. Prispevek opisuje simulacijo magnetokaloričnega učinka (MCE) gadolinijeve plošče (Gd.), ki je glavna sestavina aktivnega magnetnega regeneratorja (AMR). Prvi del članka vključuje opis in zgodovino odkritja magnetokaloričnega učinka materialov, ki imajo take lastnosti. Nadaljevanje je COMSOL Multiphysics modeliranje glavne komponente AMR: plošče gadolinij (Gd). Simulacija magnetokaloričnih učinkov in razpršitev toplote na njegovi površini je bila narejena v COMSOL-u. Model simulira en sam korak magnetnega hladilnega cikla in ovrednoti delovanje AMR z eno ploščo. Ta študija omogoča prepoznavanje najpomembnejših značilnosti, ki vplivajo na toplotno vedenje aktivnega magnetnega regeneratorja.

1 BACKGROUND AND INTRODUCTION

Magnetic refrigeration is an environmentally friendly innovative technology with huge potential and high efficiency, based on the principle of operation of the magnetocaloric effect (MCE), which was discovered more than a century ago. The MCE occurs when applying an external magnetic field to a material, a change in the thermodynamic state occurs, and a certain temperature of the magnetocaloric material (MMC).

The conversion of magnetocaloric energy is based on MCE technology . In the absence of a magnetic field, the magnetic movements in the material are disordered. If a magnetic field is applied to the material, the magnetic moments will be forced to align in a certain order; consequently, the magnetic entropy will decrease. Due to these magnetocaloric properties of the given material, it makes it reliable and efficient for magnetic refrigeration equipment, due to the reversibility of the processes and the low intrinsic entropy losses. Under isoentropic (adiabatic) conditions, the total entropy will remain constant. Therefore, the low magnetic entropy will be manifested by an increased network entropy. The atoms in the material will begin to vibrate more intensely, and, as a result, the temperature of the magnetic material will increase. The opposite occurs when the magnetic field is removed: the magnetic entropy is increased and the temperature decreases. On this basis, it is possible to create energy conversion cycles by applying different thermodynamic processes.

For refrigeration at room temperature, which is shown in this paper, the first experimental installation that produces artificial cold based on the operating principle of the magnetocaloric effect (MCE). The oldest thermodynamic studies of the magnetocaloric effect at or above ambient temperature began in the 1950s and 1960s. In addition to some cryogenic applications, investigations were initially focused on developing heat engines for the generation of useful energy. The researchers analysed different thermodynamic cycles of magnetic energy generation and their specific processes. Their work was based on that of Tesla, *[1]*, and Edison, *[2]*, who had patented ideas for “pyromagnetic generators”. At that time, electric coils were used as sources for magnetic fields. However, there is no evidence that such devices were ever built.

In the late 1950s, one of the first thermodynamic analyses of magnetocaloric energy generation was presented by Brillouin and Iskenderian, *[3]*, which was soon followed by other reports, *[4-7]*. While most of these investigations considered magnetocaloric materials in their solid form, in the 1960s, there was great interest in the idea of producing magnetic energy generators by using magnetocaloric suspensions as working fluids.

Most of this pioneering work was done by Resler and Rosensweig, [*8,9].* Subsequent work in the 1980s considered magnetocaloric energy generators based on solid working materials, *[10-12].* There is no evidence that a real prototype device for power generation has been developed. With the discovery of the high-amplitude magnetocaloric effect in 1997, *[13]*, which was followed by a series of prototypes for refrigerators, magnetic, magnetocaloric, and electricity generation again became an interesting topic.

With the growing concerns regarding global warming, there is an increase in demand for energy-efficient and environmentally efficient technologies/installations, and magnetic refrigeration is among them. Following the experimental tests, the magnetic refrigeration equipment reached a performance coefficient varying between 3 and 10 (COP) which corresponds to the efficiency of the Carnot Cycle from 15% to 75%. This energy efficiency has the potential to reduce energy consumption significantly. Thus, magnetic refrigeration has a huge potential to reduce global energy significantly and therefore limit CO_2 emissions.

This technology is environmentally friendly while conventional refrigeration uses large amounts of hydrofluorocarbons (HFCs) and chlorocarbons (CHF), which are some of the main substances that contribute to the destruction of the ozone layer and global warming. To meet this problem and solve it, in part, comes magnetic refrigeration, which using a solid refrigerant eliminates the use of freons. To obtain the maximum efficiency of the presented installation and to minimize the costs, the operation of the magnetic refrigeration systems is indicated.

2 BOUNDARY CONDITION

The modelling and simulation of the processes were performed in COMSOL Multiphysics, and a three-dimensional (3D) model was drawn using the secondary geometry tab of the given software. The detailed geometries are shown in Figure 1 (see below).

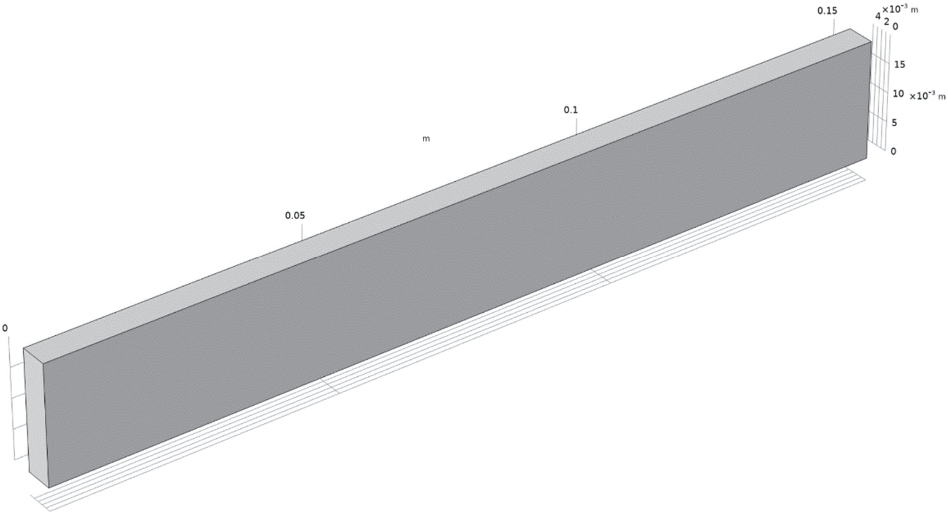

Figure 1: *COMSOL Multiphysics 3D model for simulation*

The length of the fluid channel is 15 cm, and the height is 0.5 cm and the width is 2 cm. The gadolinium plate (Gd) is placed in the centre of the regenerator and was modelled as CHEX and HHEX. The table below shows the full dimensions of the model.

Table 1: *Dimensions and parameters of the model modelled in COMSOL Multiphysics.*

L	15[cm]	0.15m
b	0.5[cm]	0.005m
W	2[cm]	0.02m

3 MODELLING AND SIMULATION

This modelling is mainly based on the study of the plate of magnetocaloric material (Gd). In different magnetization conditions and under a magnetic induction with different values, the modelling was done with the COMSOL Multiphysics software, which requires a solid knowledge of engineering principles. The purpose of this modelling is the development of the solid working agent with subsequent possibilities of developing an AMR with high efficiency, precise and fine details, as well as an advantageous price. With the help of computerized calculations, the numerical solution of the problem was obtained, which is useful and beneficial for the design study, as well as for the development of the parameters/phenomena. As a result, the method adopted in this research is to simulate the magnetocaloric phenomena on the gadolinium material (Gd) under different magnetic inductions. The thermodynamic study of Gd largely depends on the heat transfer and the efficiency of the parameters.

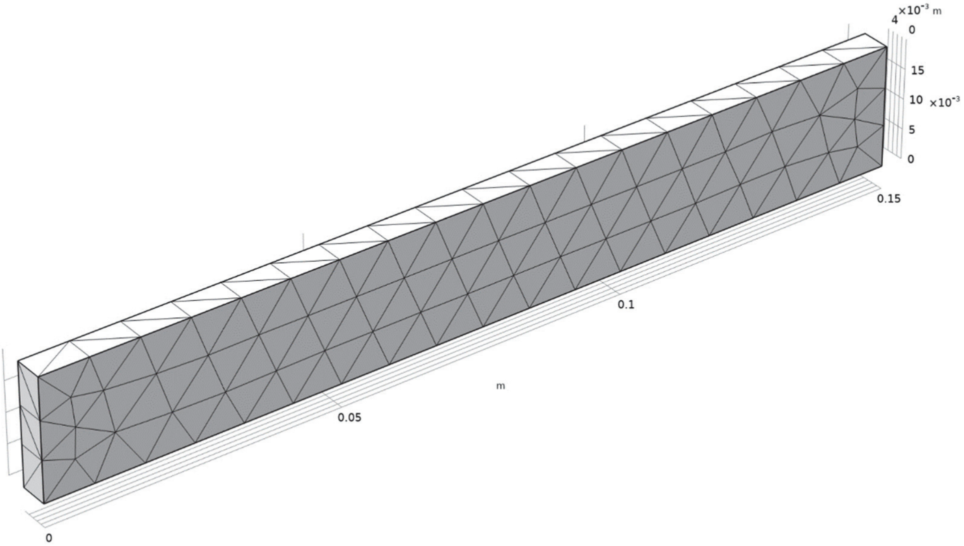

Figure 2: *3D MESH model, used for simulation*

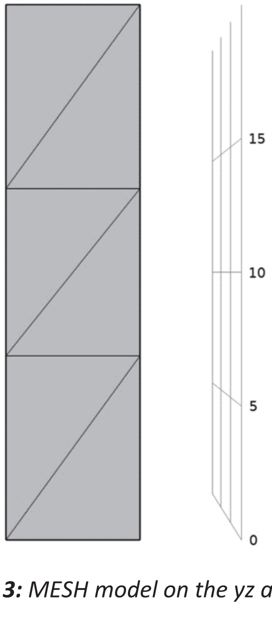

Figure 3: *MESH model on the yz axes*

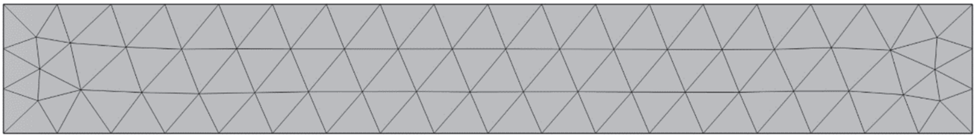

Figure 4: *MESH model on the xz axis*

The thermodynamic analysis of the entire magnetic refrigeration system defines the relations for the induction of the applied magnetic field, its entropy and the temperature variation. It should be noted that all the above-mentioned methods are part of the advanced research publications.

4 MATHEMATICAL MODELLING, HEAT, MECHANICAL WORK, AND THERMODYNAMIC RELATIONS

Entropy depends on the magnetic field (H) and temperature (T), in this case, the magnetocaloric material (Gd). Maxwell's equations represent the relationship between the magnetic field (H), the plate temperature of gadolinium magnetocaloric material (T) and its entropy (S).

$$\left(\frac{\partial S(T,H)}{\partial H}\right)_T = \left(\frac{\partial H(T,H)}{\partial T}\right)_H \tag{4.1}$$

Integrating the above equation, we obtain the relation for the isothermal conditions.

$$\Delta S_m(T,\Delta H) = \int_{H_1}^{H_2} \left(\frac{\partial H(T,H)}{\partial T}\right)_H dH \tag{4.2}$$

Mechanical work:

$$\mathrm{dw} = -\mu_0 \mathrm{HdM} \tag{4.3}$$

The derivative of the specific total entropy (for isobaric and isochoric conditions) can be defined in the present case as:

$$ds(T,H) = \left(\frac{\delta s}{\delta T}\right)_H dT + \left(\frac{\delta s}{\delta H}\right)_T dH \tag{4.4}$$

The change of entropy in the isothermal process can be defined as follows:

$$ds(T,H) = (\frac{\delta s}{\delta H})_T dH = \mu_0 (\frac{\delta M}{\delta T})_H dH \tag{4.5}$$

For a certain increase (or decrease) of the magnetic field on the Gd plate, between the two states of the different magnetic fields under isothermal conditions, the change in isothermal entropy is defined as follows:

$$\Delta s = s_2 - s_1 = \int_{H_1}^{H_2} (\frac{\delta s}{\delta H})_T \, dH \tag{4.6}$$

$$\Delta s = \int_{H_1}^{H_2} \mu_0 (\frac{\delta M}{TH})_H \, dH \tag{4.7}$$

Another important parameter for characterizing the plate of magnetocaloric material (Gd) is the change in adiabatic temperature.

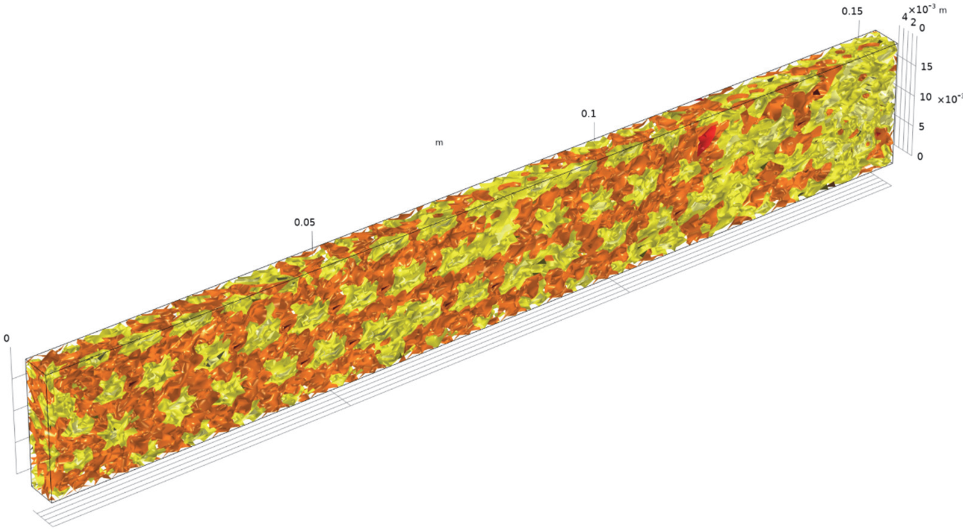

Figure 5: *COMSOL 3D model of the Gd plate with the change of the adiabatic temperature*

This represents the increase or decrease of the temperature due to the increase or decrease of the magnetic field in the absence of heat flux (adiabatic magnetization or demagnetization).

In the adiabatic process, the total specific entropy does not change (ds = 0).

$$(\frac{\delta s}{\delta T})_H dT = -\left(\frac{\delta s}{\delta H}\right)_T dH = -\mu_0(\frac{\delta M}{\delta T})_H dH \tag{4.8}$$

Figure 6: *COMSOL model of Gd board. with the change of the adiabatic temperature on the yx axis*

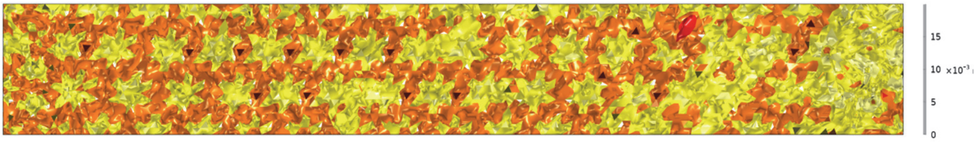

Figure 7: *COMSOL model of Gd board. with the change of the adiabatic temperature on the xz axis*

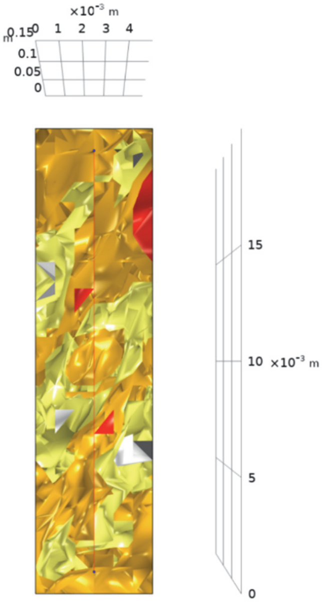

Figure 8: *COMSOL model of Gd. Board with the change of the adiabatic temperature on the yz axis.*

5 RESULTS AND DISCUSSION

The developed numerical model is a very important component for the analysis and behaviour of the Gd plate. The optimization of the active magnetic regenerator (AMR), as well as the evolution of the temperature in the regenerator on the surface of the plate is shown in Figure 9.

We present the first results: the evolution of the temperature gradient on the total surface of the Gd plate. In the magnetization process, the temperature of the magnetic regenerator (AMR) increases due to the magnetocaloric effect. Subsequently, after the cold blow period (from CHEX to HHEX), the fluid circulates on the surface of the Gd plate, absorbing heat. In this way, the internal temperature of the regenerator decreases. After the hold blow period (from HHEX to CHEX), the magnetocaloric material is demagnetized, *[14].*

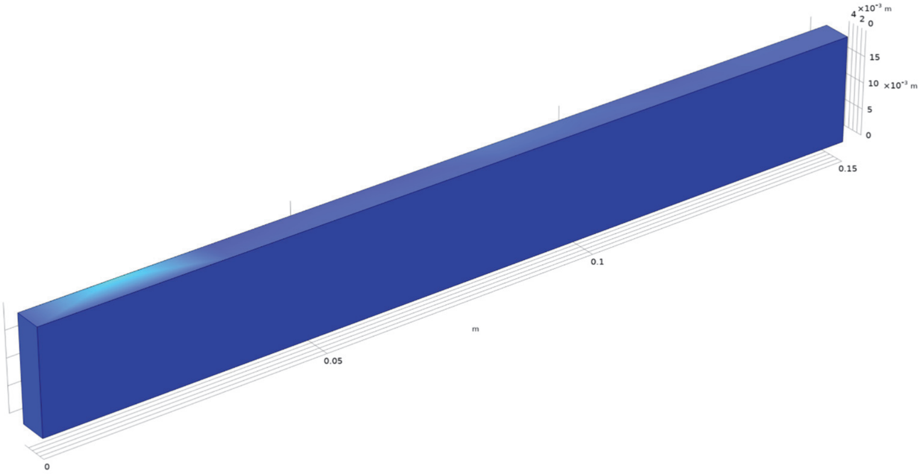

Figure 9: *3D model in COMSOL Multiphysics of the Gd plate inside the regenerator*

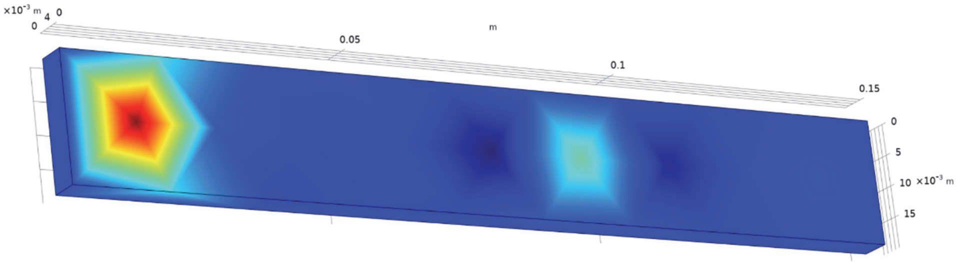

Figure 10: *3D model in COMSOL Multiphysics of Gd board used in AMR with temperature evolution*

Figure 10 shows the evolution of temperature along the length of the Gd plate. On the first centimetre of the Gd plate, a high value of the temperature in the regenerator (AMR) can be observed; it is one of the highest temperatures up to the middle of the plate (10cm). This can be explained by the fact that the variation of the temperature of the magnetocaloric material is due to the tiny variation of the applied magnetic flux and to the non-uniform conditions of the Gd plate.

In Figure 11, the evolution of the temperature variation on the whole surface of the Gd plate, inside the regenerator (AMR) and for about 60 minutes is presented.

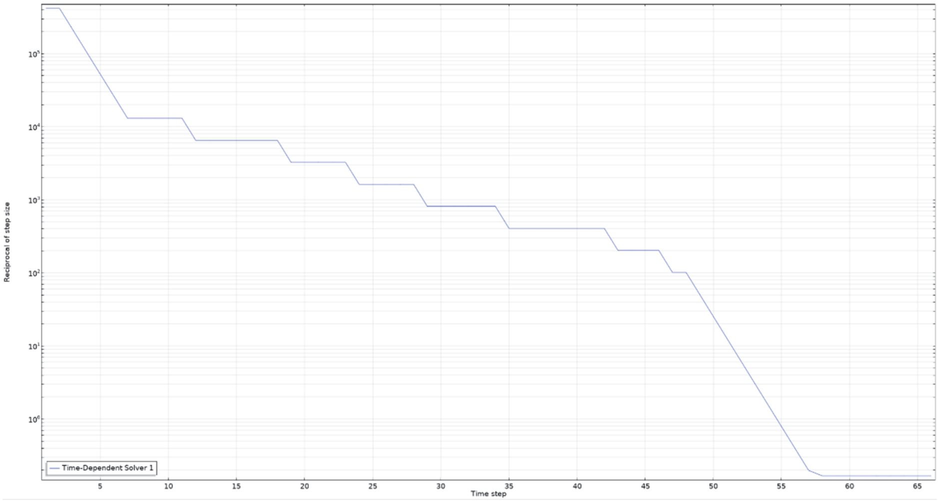

Figure 11: *Temperature variation in certain time intervals*

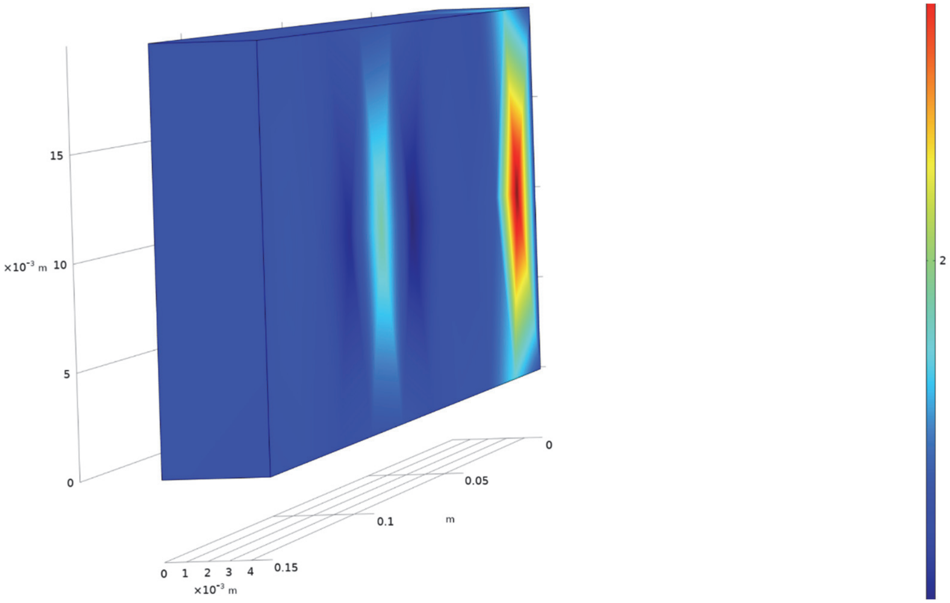

Figure 12: *COMSOL Multiphysics model of the Gd board. on the zy axis*

6 CONCLUSIONS AND PERSPECTIVES

To better understand the operation of a magnetic refrigeration system and the behaviour of the magnetic regenerator's main component, modelling was made in COMSOL Multiphysics. The modelling is based on the configuration of a gadolinium plate (Gd), which passes the heat transfer fluid with a magnetic field of 1.2 T, with the evolution of the temperature gradient on the plate's surface. The results obtained in this simulation lead to the argument that magnetic refrigeration is an innovative technology, as close as possible to being put into practice, both for air conditioning and industrial refrigeration.

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