

MODELLING OF MAGNETIC REGENERATOR AND HEAT TRANSFER AGENT IN MICROCHANNELS

MODELIRANJE MAGNETNEGA REGENERATORJA IN SREDSTVA ZA PRENOS TOPLOTE V MIKROKANALIH

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Abstract

In this article, a brief introduction of conventional refrigeration is given, followed by a description and history of magnetic refrigeration. The active magnetic regenerator comprises 12 parallel plates of magnetocaloric material (gadolinium (Gd)), through which circulates the heat transfer fluid (water, in this case). At both ends of the regenerator are the heat exchangers. The hot heat exchanger (HHEX) and the cold heat exchanger (CHEX) connects the fluid to the heat sources. The principle of operation of a magnetic refrigeration installation is based on exploiting the magnetocaloric effect from the materials that possess these properties (in this case, Gd).

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Povzetek

V tem članku je uvodoma opisano kompresorskega hlajenje, ki mu sledi opis in zgodovina magnetnega hlajenja. Aktivni magnetni regeneratorski obseg 12 vzporednih plošč magnetokaloričnega materiala (gadolinij (Gd)), skozi katerega kroži tekočina za prenos toplote (v tem primeru voda). Na obeh koncih regeneratorskega sta izmenjevalnika toplote. Vroči izmenjevalnik toplote (HHEX) in hladni izmenjevalnik toplote (CHEX) povezujeta tekočino z viri toplote. Načelo delovanja magnetne hladilne naprave temelji na izkoriščanju magnetokaloričnega učinka materialov, ki imajo te lastnosti (v tem primeru Gd).

1 BACKGROUND AND INTRODUCTION

The technology for producing artificial cold based on vapour compression was introduced more than 120 years ago, with small improvements since then, [1]. However, it has reached a technological level at which improvements and performance increases are unlikely. In 2002, they represented 25% of the total electricity consumption in residential areas and 15% of commercial electricity consumption in the US. A difficult problem to solve and quite serious with this type of technology is the refrigerant used; in most cases, it was hydrofluorocarbons (HFC), which when removed from use; this compressible gas is very harmful both for the environment as well as for the ozone layer, [2]. There is a great deal of research on the evolution and development of freons with a much lower pollution level and contribution to global warming. Previously used refrigerants, specifically chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), have had a devastating effect on the ozone layer, [3].

In this century, with the increased concern regarding global warming and increasing energy consumption, the development of a more energy-efficient refrigeration technology than steam compression is a priority, [4].

Meeting the growing demands of refrigeration and air conditioning while reducing greenhouse gases has led to further research and developments in magnetic refrigeration systems to produce artificial refrigeration. This motivation is the basis for attracting interest in many research centres in Europe, the United States, China, and Japan.

Magnetic refrigeration is based on the magnetocaloric effect of materials with this property, which manifests itself as a change in temperature when subjected to a magnetic field, [5]. This effect is reversible: when the material is no longer under the action of the magnetic field, it returns to its original state. The magnitude of the temperature change depends, in most cases, on the strength of the magnetic field. To obtain maximum energy efficiency and minimize the operating costs of this installation, it is recommended that the magnetic field source use permanent magnets, [6]. As a working agent, magnetic refrigeration uses solid materials: silicon compounds, gadolinium, etc. These materials illustrate the unique and most strongly highlighted property: the magnetocaloric effect, which is manifested by the increase/decrease of the temperature of that material when it is magnetized/demagnetized. This process of obtaining low temperatures (i.e., lower than those of the environment) have thermal conditioning as the main purpose.

2 BOUNDARY CONDITION

The modelling and simulation of thermodynamic processes were performed in COMSOL Multiphysics software. The model was inspired by specialized publications and was built using the options offered by this software. The simulated model is assumed to have a mesh model. In Fig. 1, the AMR (active magnetic regenerator) model is presented.

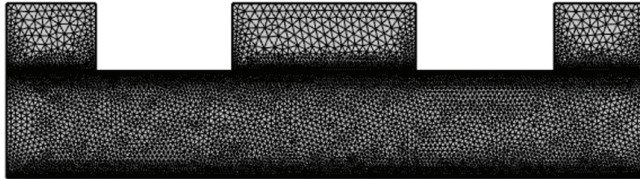


Figure 1: COMSOL Multiphysics active magnetic regenerator model used for the simulation

Heat exchangers (HHEX and CHEX) are located at both ends of the AMR. The fluid channel length of the modelled AMR is 300 mm, and the width is 10 mm. The materials were also selected according to the simulations performed in the profile publications, [7]. The AMR uses magnetocaloric gadolinium (Gd) and the assembly was made in the form of parallel plates. Water was used as a heat transfer fluid, [8].

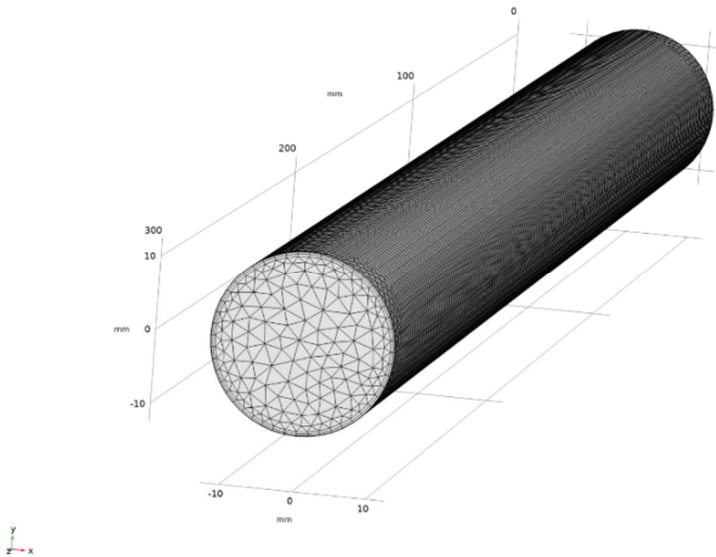


Figure 2: Mesh of the fluid channel modelled in COMSOL Multiphysics

3 MODELLING AND SIMULATION

This modelling and simulation are mainly based on the study of fluid channels inside the AMR under different magnetization conditions. The modelling was done in COMSOL Multiphysics, and the aim is to increase the efficiency of the regenerator with 12 parallel plates and to use it as a heat-transfer agent.

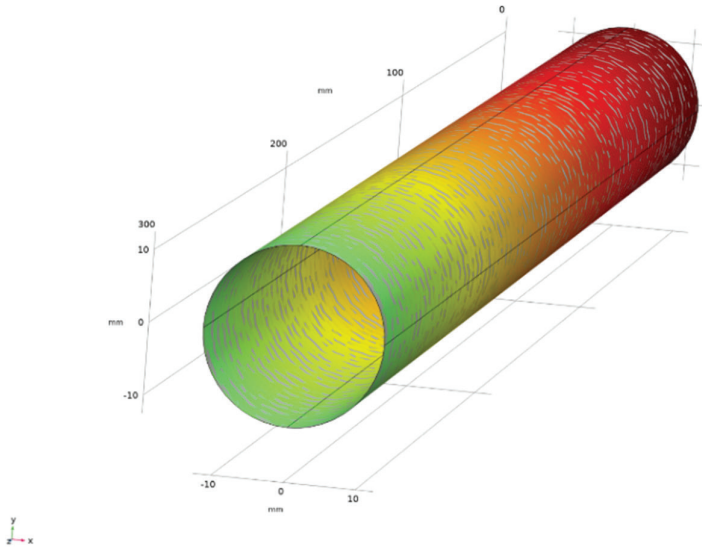


Figure 3: 3D model of the fluid channel modelled in COMSOL Multiphysics without Gd plates

The following are the geometric features of this model. The geometry is with parallel plates and microchannels through which the flow of the working agent occurs, [9].

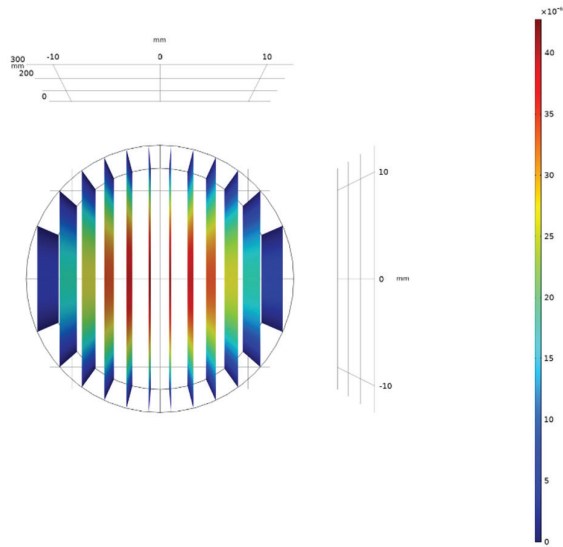


Figure 4: 2D model microchannels for heat transfer agent, modelled in COMSOL Multiphysics with Gd plates

The heat transfer fluid used in this AMR model is water, and COMSOL Multiphysics has already implemented Newtonian fluid in its library.

To avoid the oxidation of gadolinium (Gd) plates over time, various compounds can be added to the working agent (water) provided that the physical and thermodynamic properties are not significantly altered. There are different anticorrosive compounds for these types of installations.

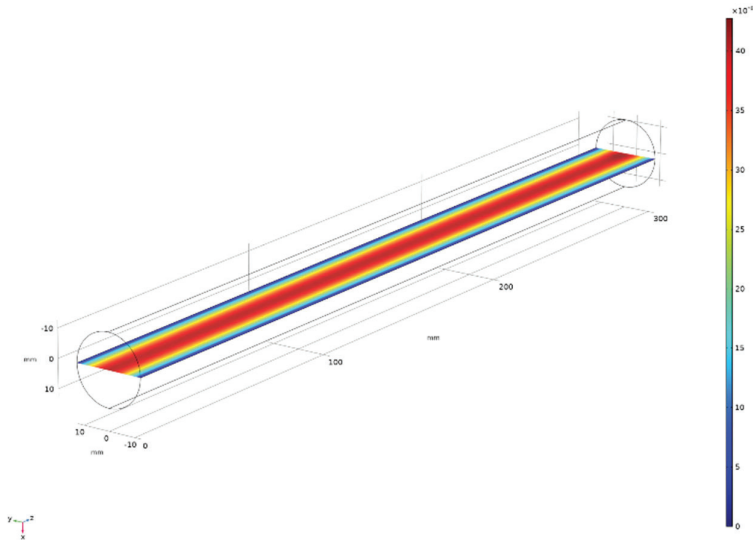


Figure 5: 3D model of fluid flow along the length of the Gd plate. inside the canal

When studying the fluid flow, the first characteristic criterion to be considered is the Reynolds number in order to determine the flow regime, [10].

$$Re = \frac{\rho_f v D_h}{\mu_f} \tag{3.1}$$

Where: ρ_f, v, μ_f are, density, speed and dynamic viscosity of the heat transfer fluid, and D_h is the hydraulic diameter.

The hydraulic diameter represents the characteristic length of the fluid flow and can be defined as:

$$D_h = \frac{4A_c}{P} \tag{3.2}$$

Where: A_c is the flow section and P , wetted perimeter

4 RESULTS AND DISCUSSION

When the heat transfer agent flows in the X direction, having been in contact with the Gd plates, which have a different temperature, the so-called hydrodynamic boundary layer appears near the solid wall. The profile below is circular, so it is possible to define an average Reynolds number, [11-12]. It can be seen how the fluid temperature drops from a maximum in the centre of the microchannel to almost zero to the boundary layer of the channel wall.

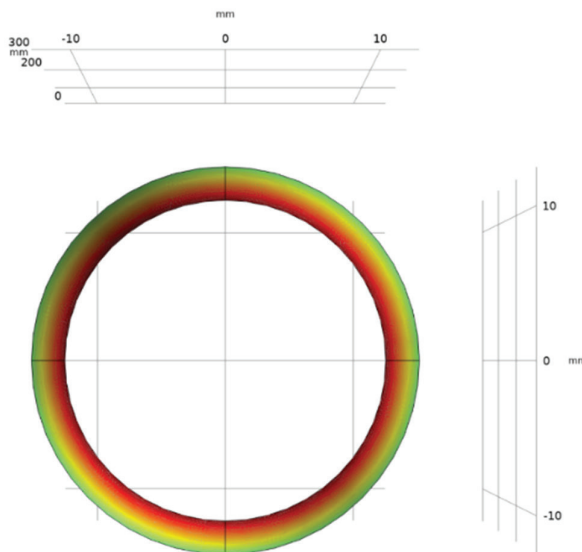


Figure 6: 2D model of the fluid channel temperature modelled in COMSOL Multiphysics

Magnetization, specific heat and adiabatic variation of the temperature of the magnetocaloric material Gd varies depending on two essential parameters: temperature and the applied magnetic field, [13].

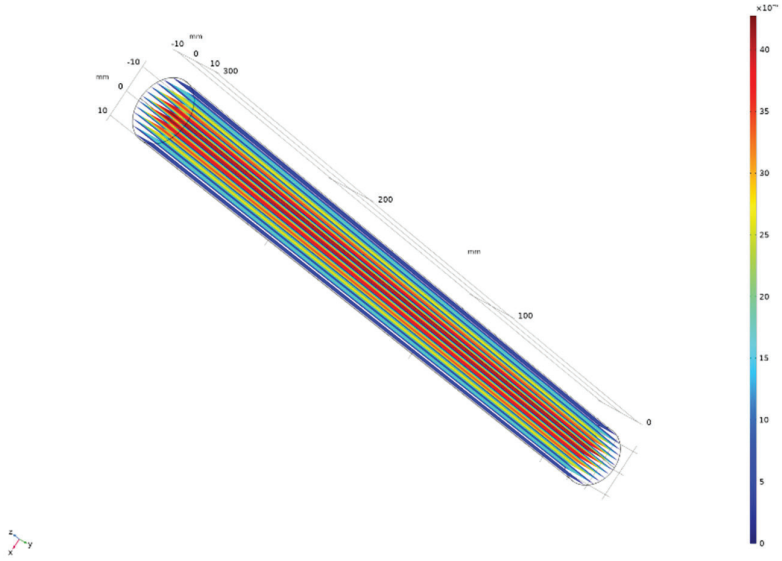


Figure 7: 3D model of the fluid channel temperature modelled in COMSOL Multiphysics with 12 parallel Gd plates

In this way, a direct application of the adiabatic temperature variation on the parallel Gd plates is obtained. At each step, the temperature of the plates made of magnetocaloric material Gd varies according to the equation below, [14]:

$$T = T(t) + \Delta T_{ad}(T(t), \mu_0 H(t), \mu_0 H(t + \Delta t)) \quad (4.1)$$

The internal energy for the plates of magnetocaloric material Gd can be written as follows:

$$U = U(S, V, H) \quad (4.2)$$

And in differential form:

$$dU = TdS - pdV - MdH \quad (4.3)$$

For the operation of the magnetic refrigeration system at constant pressure, the enthalpy can be defined as:

$$G = U - TS + pV - MH \quad (4.4)$$

And in differential form:

$$dG = Vdp - SdT - MdH \quad (4.5)$$

Fig.9 shows the variation of the adiabatic temperature of the gadolinium for a variation of the magnetic field from 2T (black line) to the maximum intensity of the magnetic field of 10T (light blue line). We can see the evolution of the values of the adiabatic temperature variation of gadolinium as a function of temperature.

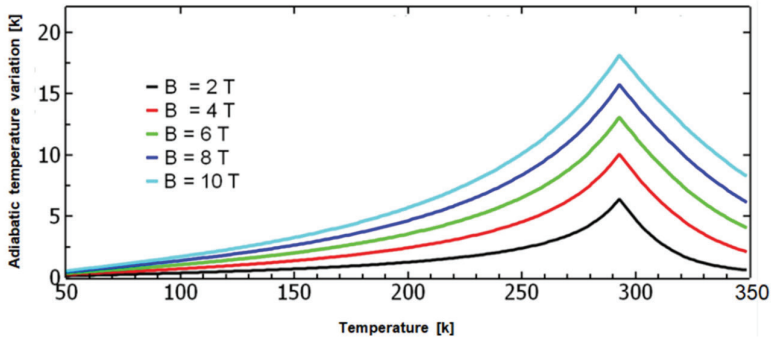


Figure 8: Variation of the adiabatic temperature of the Gd plates made with the MatLab algorithm

In Fig. 10, we can see the evolution of the entropy change of the Gd plates depending on the applied magnetic field. This variation of the magnetic field is made from 2T (black curve) to 10T (light blue curve). For all values of magnetic intensity, the evolution is slow at the beginning until the maximum value of 15 J/kgK, after which it is slowly decreasing. We observed that the contribution of electron entropy is negligible, and after Curie temperatures, the magnetocaloric material gadolinium becomes paramagnetic, [15].

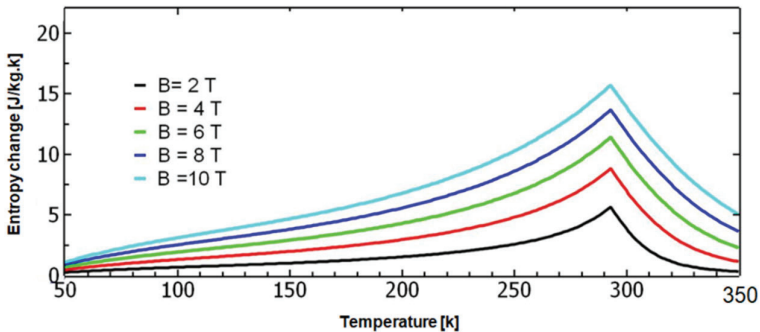


Figure 9: Evolution of the entropy change of Gd plates. performed in the MatLab algorithm

In Fig. 10 (below), one can see the 3D model simulated in COMSOL Multiphysics of the fluid channel in AMR with 12 gadolinium plates (Gd.)

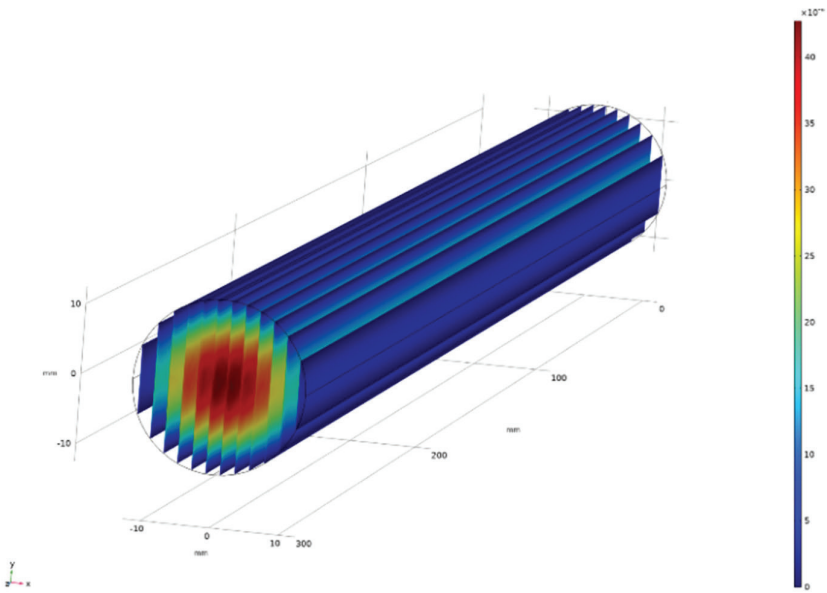


Figure 10: 3D model of the fluid channel for magnetic regenerator, modelled in COMSOL Multiphysics

5 CONCLUSIONS AND PERSPECTIVES

The first part of this paper presented the basic concepts of magnetic refrigeration and its definitions. In recent years, interest in this technology has grown considerably, due to the advantages we have shown. Then, we explained how this technology works based on magnetocaloric materials, in our case, gadolinium (Gd), which remains the reference material in this field due to its specific properties. In addition to the magnetocaloric material that is part of the AMR, the heat transfer fluid and the location of the parallel plates are quite important components. In Fig. 1 an AMR with 12 parallel gadolinium plates (Gd) was modelled. Fig. 2 shows the fluid channel mesh; 12 parallel gadolinium plates (Gd) were used. Fig. 10 shows the 3D model of the 12 gadolinium plates (Gd) in COMSOL Multiphysics, placed in parallel and water was used as a working agent. The advantages of this technology were shown with the possibility of further study of different types of AMRs: with gadolinium powder (Gd), with gadolinium spheres (Gd) and the accentuation of the modelling of heat transfer, magnetism, and convective transport of the working agent.

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Nomenclature

(Symbols)	(Symbol meaning)
AMR	active magnetic regenerator
Gd	gadolinium material
HHEX	hot heat exchanger
CHEX	cold heat exchanger