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THE PROPERTIES OF THE MATERIAL GADOLINIUM AND THE WORKING AGENT USED IN THE INSTALLATION OF MAGNETIC REFRIGERATION DEVICES

LASTNOSTI GADOLINIJA, DELOVNEGA SREDSTVA, KI GA LAHKO UPORABLJAMO V MAGNETNIH HLADILNIH NAPRAVAH

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Abstract

Much remains to be done to understand better and thus achieve better control over magnetic materials to maximize their magnetocaloric properties and performance, specifically for gadolinium. A clear path forward is highlighted by thorough experiments coupled with theory, in which the latter is tested and refined against the former, thus resulting in discoveries of new and improved materials and bringing near-room-temperature magnetic refrigeration technology to fruition in the near future.

Povzetek

V prihodnosti bo potrebno še veliko storiti, da bi bolje razumeli magnetne materiale in da bi povečali njihove magnetokalorične lastnosti in zmogljivosti. Še posebej je zanimiv gadolinij. S pomočjo nadaljnjih preizkušanj v povezavi s teorijo bi lahko razvili učinkovite magnetne hladilne naprave na osnovi magnetokaloričnih vplivov magnetnih materialov.

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1 INTRODUCTION

A considerable amount of literature has been published in which researchers have highlighted the benefits of using magnetocaloric materials for the refrigeration processes and the efficient energy-saving potential of the magnetic materials. Gao et al. studied in detail the transduction of energy in ferromagnetic and ferroic materials; moreover, the energy transduction in different types of materials such as piezoelectric, electromagnetic, and magnetostrictive materials was discussed in detail, and the relevant advantages and disadvantages were also mentioned, *[1].* In Europe and America, a massive amount of energy is wasted on refrigeration and air conditioning; by adopting an energy-efficient approach, such as magnetocaloric refrigeration or magnetic refrigeration, much of this energy can be saved, *[2].* The main reason for increased interest in magnetic refrigeration is due to its environmental friendly operation, high energy efficiency, and the absence of the need for the usage of harmful gases that cause ozone depletion and other effects that contribute to global warming, *[2].*

2 LITERATURE REVIEW

Efforts are being made for the development of a refrigerator that can work at room temperature. Various successful attempts have been made on the trial or experimental levels, such as the products developed by the companies General Electric and Haier. The properties that contribute to the refrigeration effect are due to the extraordinary response of these materials to external magnetic fields; such properties occur close to the Curie temperature, which is the temperature at which the basic inherent magnetic properties are diminished, and the material temperature is dependent upon the application of the magnetic field, *[3].* The effect has been in use since 1920, for the examination of the magnetic structure and properties of iron and other related elements, *[3].* The magnetocaloric effect was first discovered by the German physicist Warburg in 1881, *[3].* Faraday discovered that the time variation of magnetic flux results in the induction of electric currents, *[3].* Joule's research clarified the important concepts related to the electric currents and associated heat energy and confirmed that heat energy released due to flow of electromagnetically induced current is equivalent to the heat energy produced due to the electric current produced by any other source.

Moreover, it was also inferred that rapid magnetization and demagnetization results in the heating of the magnetic material due to heat energy released as a result of current flow, *[3].* Thomson inferred from the concepts of thermodynamics that the temperature-dependent property of magnetization of any material will represent or exhibit these property-related parameters in the form an increase or decrease in temperature, *[3].* The accurate, quantifiable measurement of the magnetocaloric effect of iron was possible long after the discovery of related phenomena, *[3].*

Issues related to high temperature made the measurement of the related parameters challenging. The heat-based electric motor was presented and produced by Tesla, Edison, and Stefan, *[3].* Weiss and Langevin separately contributed considerable knowledge and understanding about temperature ranges, magnetization, and hysteresis, *[3].* The initiation of studies on low temperature that had ultimately led to the realization and theoretical formulation of refrigeration was independently reported by Debye and Giauque, who demonstrated that adiabatically demagnetized paramagnetic salts result in the attainment of low temperatures; Giauque and MacDougall showed the very low-temperature achievements with such salts, *[3].*

All the work reported above resulted in the development of the foundation for the concepts of the building and understanding of magnetism, temperature, and material properties. Pecharsky et al. reported that the magnetic dipole moments of Gd could be aligned at room temperature (294 K), and highlighted that the continuous magnetic refrigeration was experimentally shown by the Collins and Zimmerman, who tested magnetic refrigerators operating at very low-temperature ranges, *[4].*

Zimm and DeGregoria explained the basic mechanism of the active magnetic regenerator cycle, *[4].* Kitanovski et al. highlighted that the there is a need to develop new thermodynamic cycles that can explain the magnetic refrigeration phenomena accurately and comprehensively; they also reported many publications about the Bryton and Ericsson's cycle associativity with the magnetic refrigeration. Moreover, active magnetic regenerators with various thermodynamic cycles were analysed, and numerical simulation of AMR was also performed using the finite element method, *[5]*. The AMR operating on the Brayton cycle resulted in the production of highest cooling power capability, while AMR operating on the Ericsson cycle is the most efficient one, *[5]*; they also mathematically explained the numerical aspects of AMR simulation. Wolf et al. provided a quantum-based explanation of the magnetocaloric effect and proposed an increase in the change in the entropy with respect to change in the magnetic field close to magnetically achieved quantum-critical point by the accurate and precise measurement of calorimetric effect, *[6].*

Noume et al. used COMSOL of simulation of the magnetocaloric effect for the designing of the magnetic regeneration cycle for the electric vehicles, *[7].* As an electric vehicle operates on the battery, in the simulation performed, the fluid flow (mainly laminar), heat transfer in solids and fluids was used, and the velocity, temperature, and heat transfer coefficient were studied *[7].* The primary equation used for the fluid flow is the Navier-Stokes equation; the energy equation, along with the heat transfer equations, were mainly used, *[7].* Gobi and Sahu used COMSOL to perform the exploratory study of the magnetocaloric effect on three different materials; these materials were gadolinium and two other different alloys for the evaluation of the final temperature of the magnetic material; the gadolinium showed the adiabatic temperature difference of 12 K, which was the highest among the studied material, *[8].* An application was developed with a graphical user interface (GUI) so that the user can input different variables, and visualize the contours of temperature and other variables.

The comprehensive literature review has been performed in this study for understanding the main developments in the selected domain. Moreover, the phenomena were also explained in detail to develop a sense of understanding. The research and publication trend in the field of magnetocaloric effect has significantly increased by the end of the 20th century due to the need for energy-efficient refrigeration and air-conditioning systems. The focus of the literature study was to report the relevant findings related to phenomena and an exploration of the numerical formulation aspects of the magnetocaloric effect. The scientific literature available on the topic of magnetocaloric effect can be subdivided into many types for the relevancy and domain specification. These categories are material-oriented, mathematical based, experiment-based, numerical based, and thermodynamic based.

This material-oriented study is focused on the determination of material constants, material properties, substructures, and orientation of the dipole moments. The research on the material aspects yields important insights about the atomic level sub-phenomena under the domain of main magnetocaloric phenomena. The mathematical study is more equation oriented, in which mathematical techniques are employed to explain the physics of the phenomena. These study methods are valuable in terms of quantification of the variables and developing valid mathematical relations.

3 BOUNDARY CONDITION

The boundary condition of the magnetic field is Ampere's law, which was applied to the regenerator, and the magnetization condition was defined. The magnetization model was applied, and the material was declared as solid; the value of the magnetization defined was 222,000 A/m in the x and y directions, and the values of electrical conductivities and relative permittivity were derived from the material. Magnetic insulation was also applied at the relevant boundaries.

The process modelling and simulation was performed in COMSOL multi physics. The model was drawn in 2D and was inspired by the research performed by the Noume et al., *[7]*, and Hsieh et al., *[9].* The 2D model was drawn in the Comsol model builder geometry, shown in Fig.1

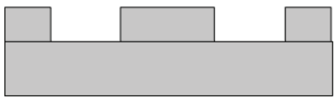

Figure 1: *Comsol 2D model used for the simulation of the magnetocaloric effect*

The length of the fluidic channel is 15.024 cm, while the height of the fluidic channel was kept as 2.5 cm. The magnetic regenerator has been placed at the centre of the channel, and the width and height of the magnetic regenerator were kept as 4.3 cm and 1.5 cm respectively. The right side square box was modelled as a hot heat exchanger, and the left side box was modelled as a cold heat exchanger. The width and height of both heat exchangers are 1.5 and 2.1 cm, respectively.

4 PROPERTIES OF COPPER MATERIAL

The experimental study is based mainly on testing of the magneto-calorific material under different magnetization conditions, equipment development for the measurement of more accurate and fine details, magnetic refrigerator prototype development, and similar. This study involves the sound knowledge of engineering principles.

Table 1: *Show the material properties of the copper in the Comsol*

No.	Material properties off copper			
1	µ	1	[H/m]	Basic
2	ρ	5.998	[S/m]	Basic
3	C	385	J/(kg·K)	Basic
4	e	1	F/m	Basic
5	r	8940	kg/m³	Basic
6	c	400	W/(m·K)	Basic
7	m	1	Pa·s	Basic
8	e	0.5	Ib,w(T)	Basic
9	E	126	Pa	Basic
10	n	0.34	-	Basic
11	r	1.667	Ω·m	Linearized
12	j	3.862	1/K	Linearized
13	T	295.15	K	Linearized

The numerical study is dependent upon the numerical solution of the problem, mainly obtained with the help of computer calculations. The method is useful and beneficial for the parametric design study, and detailed understanding of phenomena. Therefore, the study method adopted in this research is the numerical simulation of magneto-calorific phenomena. The thermodynamic study is mainly dependent upon the heat transfer and thermodynamic analysis of the cycles, systems, and subsystems. The thermodynamic analysis defines the relations for the magnetic field, entropy, and temperature change. It must be mentioned that all study techniques above are usually part of a research publication; however, if the literature is deeply analysed, the research is more inclined towards one of these methods.

The materials were also selected according to the simulations performed by Noume et al., *[7]*, and Hsieh et al. *[9].* The magnetic regenerator placed in the centre was allotted the gadolinium material, the fluid used in the simulation is water, and the plates used to model the heat exchanger are composed of copper. The material properties of copper used in the simulation, along with COMSOL operators, are shown below.

5 PROPERTIES OF WATER-WORKING AGENT

Table 2: *Properties of water agent in Comsol*

No.	Properties of water-working agent			
1	µ	1	[H/m]	Basic
2	ρ	5.9987	[S/m]	Basic
3	C	385	J/(kg·K)	Basic
4	e	1	F/m	Basic
5	r	8940	kg/m^3	Basic
6	c	400	W/(m·K)	Basic
7	m	1	Pa·s	Basic
8	e	0.5	Ib,w(T)	Basic
9	E	126.9	Pa	Basic
10	n	0.34	-	Basic
11	r	1.6678	Ω·m	Linearized
12	j	3.8623	1/K	Linearized
13	T	295.15	K	Linearized

The properties used for gadolinium mostly consist of 3×3 matrices, which are difficult to show here as such. The operators, along with units and properties, are shown below in Table 1.

6 PROPERTIES OF GADOLINIUM MATERIAL

Table 3: *The properties mostly used for gadolinium*

No.	The properties used Gadolinium material	
1	Thermal conductivity	Basic
2	Heat capacity at constant pressure	Basic
3	Electrical conductivity	Basic
4	Density	Basic
5	Relative permittivity	Basic
6	Dynamic viscosity	Basic
7	Resistivity	Basic
8	Coefficient of thermal expansion	Basic
9	Local property HC	Local pr.
10	Local property VP	Local pr.
11	Local property TD	Local pr.
12	Relative permeability	Basic
13	Tangent coefficient of thermal ex.	Thermal
14	Thermal strain	Thermal
15	Isotropic tangent coefficient of ther.	Thermal
16	Isotropic thermal strain	Thermal

The physics selected for the simulations are the main determinants of the solution and boundary conditions. The models used in the simulation are magnetic fields, heat transfer in solids, heat transfer in fluids, and laminar flow for the fluidic solvers. All these have been combined to determine a numerical solution to the magnetocaloric effect problem. COMSOL multi physics excellently combines the physics to formulate a multi physics problem, and the user-friendly interface allows the user to add multiple studies within one window. The proposed multi physics based on different physics selected are also shown in the multi physics tab, and the option is provided to apply it on different domains and boundaries. All the previously defined steps allow the user to define the problem comprehensively.

7 RESULTS

Figure 2 shows the temperature profile. At t=0 sec, the temperature slowly starts dissipating due to the convection effects in the fluid.

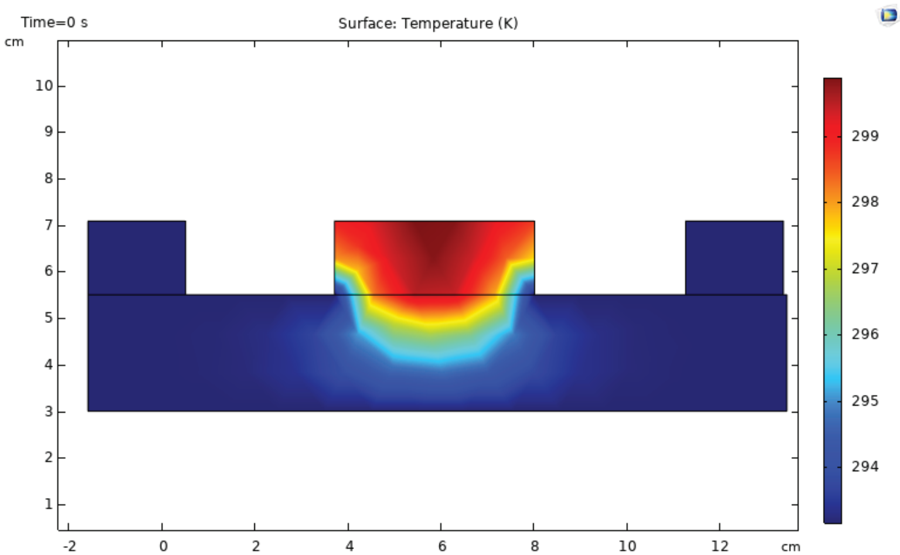

Figure 2: *Temperature of the fluid and the regenerator has been raised*

The values of the temperature are almost the same as that obtained by the Noume et al. in their simulations, *[14].* The temperature rise due to the magnetocaloric effect is similar in magnitude to that has been reported in the literature.

Successful simulations have been performed by using the simplified model techniques and methods. For a more realistic analysis, a transient approach should be adopted. The laminar flow approach has also been adopted in order to reduce the complexity of the solution procedure; otherwise, the flow may be considered turbulent due to heat transfer and fluid flow in the current scenario. The material chosen for the study is widely used in the research of magnetocaloric materials.

8 CONCLUSION

In this article, the process modelling and simulation was performed in Comsol multi physics. The study of gadolinium is focused on the determination of material constants, material properties, substructures and orientation of the dipole moments; the research on the material aspects give important insights about the atomic level sub-phenomena under the domain of main magnetocaloric phenomena. The experimental study is based mainly on-testing of the magneto-caloric material under different magnetization condition equipment, development for the measurement of more accurate and fine details, magnetic refrigerator, prototype development and similar. This study involves the sound knowledge of engineering principles. The simulation started with the magnetization of the material by using the boundary condition of Ampere's law, which was governed by the magnetic field module. The next step was based on the heat transfer due to the magnetocaloric effect resulting in the temperature rise of the material; the heat begins to transfer into the liquid water, which the final step is based on the flow of the water and resulting in the removal of the heat energy, which is controlled by the laminar flow module.

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Nomenclature

t	time
ρ	density
Q	heat released