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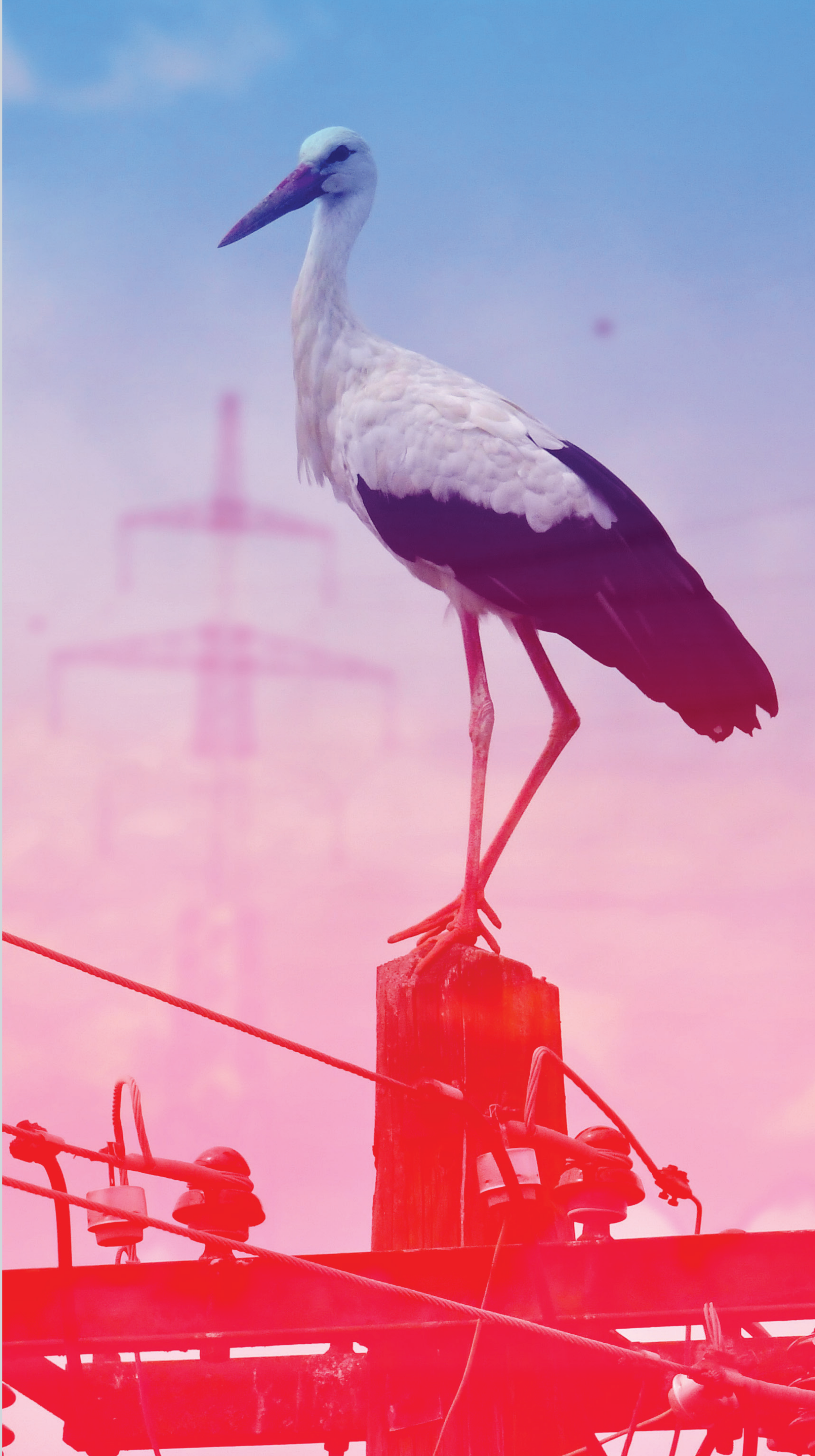

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Spoštovani bralci revije Journal of energy technology (JET)

Procesi hlajenja in ogrevanja so izjemnega pomena za celotno družbo, saj vplivajo na počutje človeka, kot tudi na procese v industriji. Eden od sodobnejših načinov hlajenja je gotovo uporaba tehnike magnetnega hlajenja, zato smo v aktualno številko revije Journal of energy technology uvrstili kar dva članka s tega področja. Raziskave magnetnega hlajenja, opisane v obeh člankih, so potekale na Gheorghe Asachi technical University of Iasi, Fakulteti za elektrotehniko, v Romuniji, pod okriljem prof. dr. Adriana Traiana Plesce. Imel sem privilegij, da sem prof. Plesco osebno spoznal in ga tudi povabil, da je leta 2019 preko projekta Erasmus+ obiskal Fakulteto za energetiko. Žal je prof.Plesca v mesecu februarju 2021 preminil v starosti 49 let. Odšel je na višku svoje uspešne strokovne poti in za seboj pustil veliko nedokončanega dela. Kot profesor in raziskovalec je deloval na področju električnih naprav, modeliranja in simulacijah ter toplotnih analizah v električnih napravah. Je avtor 13 knjig, 29 patentov in velikega števila znanstvenih člankov. Bil je tudi človek z veliko energije in pozitivne naravnanosti do življenja, zato je njegov odhod velika izguba tako po človeški kot tudi strokovni plati.

Jurij AVSEC
odgovorni urednik revije JET

Dear Readers of the Journal of Energy Technology (JET)

Cooling and heating processes are extremely important for the whole of society, as they affect both individual people as well as processes in industry. One of the more modern cooling methods is the magnetic cooling technique; we have included two articles about in the current issue of the Journal of energy technology. The research on magnetic cooling described in both articles was conducted at Gheorghe Asachi Technical University of Iasi, Faculty of Electrical Engineering, Romania, under the auspices of Prof. Adriana Traian Plesca. I had the privilege of meeting Prof. Plesca in person and also hosted him when he visited the Faculty of Energy in 2019 through the Erasmus+ project. Unfortunately, he passed away in February 2021 at the age of 49. He passed away at the height of his successful career and left behind a lot of unfinished work. As a professor and researcher, he worked in the field of electrical devices, modelling and simulations, and thermal analysis in electrical devices. He was the author of 13 books, 29 patents and a large number of scientific articles. He was also a man full of energy and a positive attitude towards life, so his departure is a great loss from both the human and professional points of view.

Jurij AVSEC
Editor-in-chief of JET

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ANALYSIS OF COMBUSTIBLE FRACTIONS IN MIXED MUNICIPAL WASTE AND PACKAGING AND CALCULATION OF ENERGY VALUE

ANALIZA GORLJIVIH FRAKCIJ V MEŠANIH KOMUNALNIH ODPADKIH IN EMBALAŽI TER IZRAČUN ENERGIJSKE VREDNOSTI

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Keywords: mixed municipal waste, mixed municipal packaging, combustible fractions, energy value, solid recovered fuel, TGA analysis

Abstract

The present article analyses combustible fractions in mixed municipal waste and packaging and the calculation of energy value. Methods of thermal treatment of waste and methods of preparation of alternative fuels and classifications are presented and described. The article describes the method of analysis of caloric values with which we determined the energy values of individual fractions. For the research, we also used two thermal analyses, with which we considered individual fractions, thermogravimetric analysis, and differential dynamic calorimetry. The article presents the results of both thermal analyses, with which we observe the responses of individual types of plastics at different

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temperatures and the change in physical and chemical properties. The problem we have analysed in this article is mainly recyclable plastic that can no longer be reused due to various factors. The results of the structural analysis of household waste collection are also presented and described; on the basis of the analysis, the energy value of the container of mixed municipal waste and the reasonableness of waste reuse are recalculated.

Povzetek

Članek obravnava analizo gorljivih frakcij v mešanih komunalnih odpadkih in embalaži ter preračun energijske vrednosti. Predstavljeni in opisani so načini termične obdelave odpadkov ter metode priprave alternativnih goriv in klasifikacija. V članku je opisana metoda analize kaloričnih vrednosti, s katero smo določali energijsko vrednost posameznih frakcij. Za namen raziskave smo uporabili tudi dve termični analizi, s katerimi smo obravnavali posamezne frakcije, termogravimetrično analizo in diferenčno dinamično kalorimetrijo. V članku so predstavljeni rezultati obeh termičnih analiz, s katerimi opazujemo odzive posameznih vrst plastike pri različnih temperaturah ter spremembo fizikalnih in kemijskih lastnosti. Problematiko, ki smo jo analizirali v tem članku, predstavlja predvsem plastika, ki se lahko reciklira, vendar je zaradi različnih dejavnikov ni mogoče več ponovno uporabiti. Predstavljeni in opisani so tudi rezultati strukturne analize zbiranja odpadkov v gospodinjstvih in na podlagi analize preračuna energijska vrednost zabojnika mešanih komunalnih odpadkov ter smiselnost ponovne uporabe odpadkov.

1 INTRODUCTION

Waste overcrowding is a major issue today. Ways to prevent the accumulation of waste material effectively are being sought. Utility companies collect waste in their collection centres. Waste material is classified according to its usability (and non-usability). At the same time, great emphasis is placed on the field of recycling. For the most part, the public is insufficiently aware of waste separation and the method of proper separation. There are several types of waste separation and collection. Collection begins with an ordinary household, for which purpose mixed municipal waste and mixed packaging. In some cases, bio-waste is separated in the first phase. With the right approach to waste management, we can contribute significantly to reducing the accumulation of waste and waste materials. Through detailed analyses and studies, waste can be separated to such an extent that it is reused, and disposed of as little as possible. Waste is also strictly defined according to legislation, and the consequent management of all types of waste differs at local, regional, and national levels. These classifications help in planning and defining methods of waste separation and collection. The reuse or recycling of waste requires precise information on the source and composition, the means and strategy of management can be determined. The definition of waste, of course, facilitates its classification into different groups, but such classification extremely demanding due to the diversity of waste, but only in this manner can it be handled consistently. Due to the heterogeneity of the waste material, we must strive for further homogenization.

1.1 Waste issues in Slovenia

In Slovenia, the amount of waste is increasing every year; about 8 million tons of waste are generated annually. The largest share is accounted for by construction waste, specifically, 59%; waste from thermal processes represents about 13%, waste from metal and wood processing accounts for 7%, and waste is also generated in waste management facilities themselves (about 4%). Other types represent 5% of all generated waste. Municipal waste represents approximately one million tons, which is 12.5% of all waste and means that the population of Slovenia generates an average of 495 kilograms per person of waste per year. In the past, most waste was disposed of in dedicated landfills. With municipal waste management centres, the trend of waste disposal is significantly reduced as the recycling rate has increased. In Slovenia, about 59% of all municipal waste is recycled, *[1].*

1.2 Types of waste that can be used for alternative fuels

Annex 7 of the Waste Management Regulation (1358), page 3194, *[2]*, describes the division of waste into individual types. The waste classification list is divided into 20 groups, as can be seen in Table 1. The source of the waste must be identified for classification.

Table 1: *Waste classification [2]*

1	Wastes from prospecting, mining, quarrying, physical and chemical processing of mineral resources
2	Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing
3	Wastes from wood treatment and processing and production of particleboard and furniture, fibre, paper, and board
4	Wastes from the leather, fur, and textile industries
5	Wastes from oil refineries, natural gas refining, and coal pyrolysis
6	Wastes from inorganic chemical processes
7	Wastes from organic chemical processes
8	Wastes from manufacture, formulation, supply and use of surface preservatives (paints, varnishes and enamels), adhesives, sealants, and printing inks
9	Wastes from the photographic industry
10	Wastes from thermal processes
11	Wastes from chemical treatment and surface protection of metals and other materials; hydrometallurgy of non-ferrous metals
12	Wastes from shaping processes and physical and mechanical surface treatment of metals and plastics

13	Oil wastes and wastes from liquid fuels (excluding edible oils referred to in points 05 and 12)
14	Waste organic solvents, refrigerants and propellants (excluding 07 and 08)
15	Packaging waste; absorbents, cleaning cloths, filter media and protective clothing not elsewhere specified or included
16	Wastes not otherwise specified in the classification list
17	Construction and demolition wastes (including excavations from contaminated sites)
18	Wastes from health or veterinary medicine and/or related research (excluding wastes from kitchens and restaurants not directly derived from health or veterinary medicine)
19	Wastes from waste treatment facilities, treatment plants and from the preparation of drinking water and water for industrial use
20	Municipal waste (household and similar wastes from trade, industry and the public sector), including separately collected fractions

Wastes that can be used in processing for alternative fuels are in groups:

- 04 01 09 wastes from finishing and finishing of fur and leather,
- 07 02 13 Waste plastics,
- 15 01 01 Paper and paperboard packaging,
- 15 01 02 Plastic packaging,
- 15 01 06 Mixed packaging,
- 17 09 04 Mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02, and 17 09 03,
- 19 12 12 Other wastes (including mixtures of materials) from mechanical treatment of waste other than those mentioned in 19 12 11
- 20 01 01 Paper and paperboard
- 20 01 39 Plastic,
- 20 03 01 Mixed municipal waste,
- 20 03 07 Bulky waste, *[3].*

Products of alternative fuel production are most often classified as:

- 19 12 10 Combustible waste (fuel derived from waste),
- 19 12 12 Other wastes (including mixtures of materials) from mechanical treatment of wastes other than those mentioned in 19 12 11, *[3].*

2 WASTE MANAGEMENT AND TREATMENT

The preparation of an alternative fuel requires a multi-stage treatment to achieve the desired quality. High-calorie fuel is used in primary kilns or cement plants. The preparation of this fuel takes place in the process of sorting waste material. To achieve the efficiency of the sorting process, it is necessary to reduce the dimensions of the material and then separate it into 2D and 3D material. 3D material often contains several impurities in the form of heavy metals and larger pieces of building material. Also, 3D material is more demanding for mechanical processing. In the first step, magnetic separation, it is necessary to eliminate materials containing iron (Fe). This is followed by Eddy current separation to remove non-ferrous metals. Prior to the grinding process, air separation in an air separator is required to maintain the quality of the solid fuel, as all remaining heavy fraction is eliminated in this process. The particle size of the solid fuel is determined by the acquirer. Materials are usually ground to a size >30 mm. A similar separation procedure is used for 2D materials, *[4].*

2.1 Heat treatment of waste

Incineration or co-incineration is used for different types of waste. Heat treatment is only part of the complex waste treatment technology used to generate energy or reduce waste. From the chemical point of view, the waste incineration process can be divided into three phases.

In phase one, drying and degassing takes place. This phase does not require oxygen, as it depends only on the supplied heat, *[5].* Evaporation starts in the first phase, mainly of hydrocarbons and water; it occurs between 100 °C and 300 °C. The second phase is the pyrolysis and gasification of alternative fuels or waste. Pyrolysis represents further decomposition without the presence of oxygen at a temperature between 250 °C and 700 °C. Gasification of carbon residues with water vapour and CO in residues occurs at temperatures between 500 °C and 1000 °C. In the third stage, the flammable gases formed in the first and second stages are oxidized and burned at a temperature between 800 °C and 1450 °C. This phase is called oxidation, *[5].*

2.2 Heat treatment technologies

Different types of waste also require the use of different types of heat treatment. The most common heat treatment technologies are:

- grate incinerators,
- rotary kilns,
- fluidized beds,
- pyrolysis and gasification systems.

3 ALTERNATIVE FUELS FROM WASTE

Alternative fuels and the qualification system can be defined in several ways. In addition to the values and restrictions set by the legislation for the different uses of solid fuels from waste, in practice, the composition and properties of the fuel are determined by the supplier and the user. The most important parameters for fuel are fraction size, net calorific value, sulphur, fluorine, ash content, moisture, organic carbon content as well as material density and heavy metal content in the fuel, *[6].*

Regardless of its use and method, alternative fuel from waste must meet several criteria:

- caloric values,
- low chlorine content,
- quality control,
- particle size,
- density,
- a sufficient amount of fuel with the required properties, *[6].*

3.1 Solid Recovered Fuel

Solid Recovered Fuel (SRF) is a solid fuel from waste with calorific values ranging from 11 to 25 MJ/kg. Typically, fuel is produced from high-calorie sorted mixed municipal waste and industrial waste. The size of individual fuel particles is between 5 and 300 mm, *[4].*

Table 2: *Classification of solid alternative fuels, [7]*

PARAMETERS	SHARE	UNITS	1. Class	2. Class	3. Class	4. Class	5. Class
Net calorific value	arithmetic mean	MJ/kg	≥ 25	≥ 20	≥ 15	≥ 10	≥ 3
Chlorine (Cl)	arithmetic mean	% (m/m)	≤ 0.2	≤ 0.6	≤ 1.0	≤ 1.5	≤ 3.0
Mercury (Hg)	median	mg/MJ	≤ 0.02	≤ 0.03	≤ 0.08	≤ 0.15	≤ 0.5
Mercury (Hg)	80th percentile value	mg/MJ	≤ 0.04	≤ 0.06	≤ 0.16	≤ 0.30	≤ 1.0
Cadmium (Cd)	arithmetic mean	mg/kg	≤ 1.0	≤ 4.0	≤ 5.0	≤ 5.0	≤ 5.0
Sulphur (S)	arithmetic mean	% (m/m)	≤ 0.2	≤ 0.3	≤ 0.5	≤ 0.5	≤ 0.5

There are several types of solid SRF fuel classification. They can be divided by quality (Table 3) or by using heat treatment technology (Table 4). Of course, each classification needs verified fuel quality parameters and properties.

Table 3: *Classification of different SRF-qualities, [4]*

Parameters	**SRF – specifications**						
	Coal-fired power station	**Calciner**	**Grate firing**	**Fluidized bed**	**HOT DISC cement kiln (HDF)**	**Primary burner cement kiln (PBF)**	**Blast furnace (steel plant)**
			Utility boilers				
Net calorific value MJ/kg]	11–15	11–18	11–16	11–16	14–16	20–25	< 25
Particle size [mm]	< 50	< 50–80	< 300	<20– 100	< 120	< 10–30	< 10
Oversize [%]	0	< 1	< 3	< 2	*	< 1	0
Impurities (extraneous material) [w %]	< 1	0	< 3	< 1–2	*	< 1	0
Chlorine (Cl) [w %]	< 1.5	< 0.8	< 1.0–0.8	< 1.0–0.8	0.8–0.6	< 1.0–0.8	< 2
Ash [w %]	< 35	*	*	< 20	20–30	< 10	< 10

4 POLYMERS IN WASTE AND THEIR PROPERTIES

There are many types of polymers. In waste, they are divided into seven subgroups. Some types of plastic can be recycled, while others are non-recyclable. The problem described in this article is mainly plastic that can be recycled, but due to various factors (incorrect separation, incorrect storage and use), it can no longer be recycled. Such waste in many cases ends in landfills. To reduce the disposal of non-degradable and non-reusable plastics, heat treatment is therefore essential. The largest share is represented by plastic in waste, which is used as an alternative fuel, and it also represents the raw material that in most cases has the highest net calorific value and thus increases the value of the fuel itself.

Plastic is an extremely important component. Many substances are being investigated to replace it with other raw materials, but in the short term life without it will certainly not be possible. Therefore it is extremely important that it is used for other purposes, such as obtaining energy by heat treatment. Plastics are divided according to SPI labels, and these labels help individual and waste processors to classify plastics into groups for further sorting and processing. Data on different types of plastics are presented in Table 4.

***Table 4:** Classification of plastics in waste by groups*

TYPE OF PLASTIC	SPI LABEL	USAGE
Polyethylene terephthalate (PET or PETE)	1 PETE	Drink bottles
High-density polyethylene (HDPE)	2 HDPE	Packaging for milk, cosmetics
Polyvinyl chloride (PVC)	3 PVC	Plastic wrappers, various toys, spray bottles
Low-density polyethylene (LDPE)	4 LDPE	Shopping bags, plastic covers, reusable plastic
Polypropylene (PP)	5 PP	Food packaging
Polystyrene (PS)	6 PS	Plastic cutlery, various food packaging
Other	7 OTHER	Other packaging that cannot be classified in any of the above groups

Polyethylene terephthalate (PET or PETE) or polymer PET is a type of polyester and represents one of the most important groups of packaging material, as it is widely used for packaging beverages. PET is primarily useful because of its properties. It has low density, good light transmission, resistance to elevated temperatures, good chemical resistance and dimensional stability and high toughness, *[8].* High-Density Polyethylene (HDPE) and Low-Density Polyethylene (LDPE) are the simplest polymers, at least in terms of chemical structure, which ranks them among the most represented synthetic polymers also in terms of production. They generally have high toughness, are flexible and chemically resistant, but have lower thermal stability and strength. Low and high-density polyethylenes have a characteristic low melting point. They are distinguished by density, namely HDPE ρ= 0.940–0.965 g/cm³, and LDPE density ρ = 0.915–0.940 g/cm³, *[8].* Polyvinyl chloride or PVC can be soft or hard. In connection with its properties, PVC has a high resistance to organic chemicals, and lower to heat, light and mechanical influences. PVC is an environmental problem mainly due to the content of phthalate-based plasticizers. An additional problem is the unreacted monomer in the form of vinyl chloride, which is considered to be carcinogenic, *[8].* Polypropylene (PP) is one of the lightest synthetic polymers with a density of ρ= 0.90–0.91 g/cm³. It is similar in basic properties to LDPE but has higher strength, high gloss, and a higher melting point. It is resistant to water and most organic solvents. The problem is oxidation and decomposition at elevated temperatures, *[8].* Polystyrene (PS), compared to other polymers, is slightly harder and stiffer, as well as more brittle. It is unsuitable for use at higher temperatures. It is highly susceptible to photochemical degradation in light, *[8].*

5 RESULTS

5.1 Structural analysis of mixed municipal solid waste and mixed packaging

Mixed municipal solid waste (MSW) was classified into individual fractions: plastics, paper and cardboard, textiles and footwear, wood waste, rubber, glass, metals, construction waste, electronic devices, kitchen waste, including food scraps and other discarded waste, biological waste (mostly waste landscaping) and some other waste that we could not separate. Table 5 shows the percentage of waste.

Table 5: *Quantity of individual fractions in the analysed container in MSW*

FRACTION	Quantity %
Plastic	16.5
Paper and cardboard	20.5
Textiles and footwear	3
Wood waste	4
Rubber	4.5
Glass	6
Metals	5.5
Construction waste	7,5
Electronic devices	5
Kitchen waste (food scraps and other)	17.5
Biological waste	7
Other	3
SUM	100

As part of the research, we also analysed the percentage of individual fractions in MP, using a 30 kg sample. From Table 6, we determine which fractions were in the container. Tetra packs of various packaged liquids appeared in the container to the greatest extent (31%), followed by bottles (25%), aluminium cans (22%). The fractions that remained were paper and cardboard (12%) and glass (3%). Some waste was also of biological and other origins, which belongs more to MSW (7%). We found that 43% of this packaging waste is recyclable, which means that no additional treatment is required. As much as 57% was dirty packaging that was not suitable for recycling and needed to be further processed for alternative fuels or reuse.

Table 6: *Structural analysis of MP*

FRACTION	Quantity [%]	Suitable for recycling [%]	Processing required [%]
Bottles	25	15	10
Cans	22	22	0
Tetrapack	31	2	29
Paper and cardboard	12	3	9
Glass	3	1	2
Other (MSW)	7	0	7
SUM	100	43	57

In Table 7, the MP structure was further elaborated, according to the needs of analysis in the research. Plastics were divided into seven basic groups, as presented in Table 4. We see that most packaging waste has a PET composition (47%), followed by HDPE and LDPE with 16 and 17%. Other polymers are approximately evenly represented.

Table 7: *Polymers in MP*

Type of plastic in MP	Quantity [%]
Polyethylene terephthalate (PET or PETE)	47
High density polyethylene (HDPE)	16
Polyvinyl chloride (PVC)	3
Low density polyethylene (LDPE)	17
Polypropylene (PP)	5
Polystyrene (PS)	4
Other	8
SUM	100

5.2 Samples

As part of the research, we analysed 50 samples of SRF fuel: 25 samples of fuel of lower quality and 25 samples of higher quality fuel. Gross and net calorific value and moisture content were analysed in the samples. We also performed a calorimetric analysis for the two individual most represented fractions in the structural analysis, plastic foil and cardboard. Thermogravimetric analysis and differential dynamic calorimetry were also performed for four plastic samples. In total, we analysed approximately 80 kg of waste.

5.3 Results of calorimetric analysis

For the analysis of the calorific value of waste, we used 25 samples of SRF fuel of lower quality and 25 samples of SRF fuel of higher quality. We also analysed the calorific value of the foil and cardboard in Figure 1.

Figure 1: *Photos of foil (up) and cardboard (down)*

Figure 2 (below) shows the results of the calorimetric analysis of SRF fuel of lower quality. The graph presents the results of caloric values as a function of moisture. The samples had different moisture content; it is evident that those samples that contained more moisture have a slightly lower calorific value. Values range between 12 MJ/kg and 24 MJ/kg. According to the obtained results, the fuel can be classified into the classes given in Table 4 (Classification of solid fuels). Eight samples are thus classified into the fourth quality class, sixteen samples into the third quality class, and one sample exceeds the value of 20 MJ/kg and could be classified in the second quality class. Similarly, we analysed the calorific values of SRF fuel samples of higher quality. Figure 2 clearly shows how the moisture content reduces the calorific value of the fuel. The net calorific value of the samples ranged from 10 MJ/kg to 33 MJ/kg. These samples were also divided into quality classes. In the fourth class, we add one sample, in the third three, the second class comprises eleven, and the first ten samples.

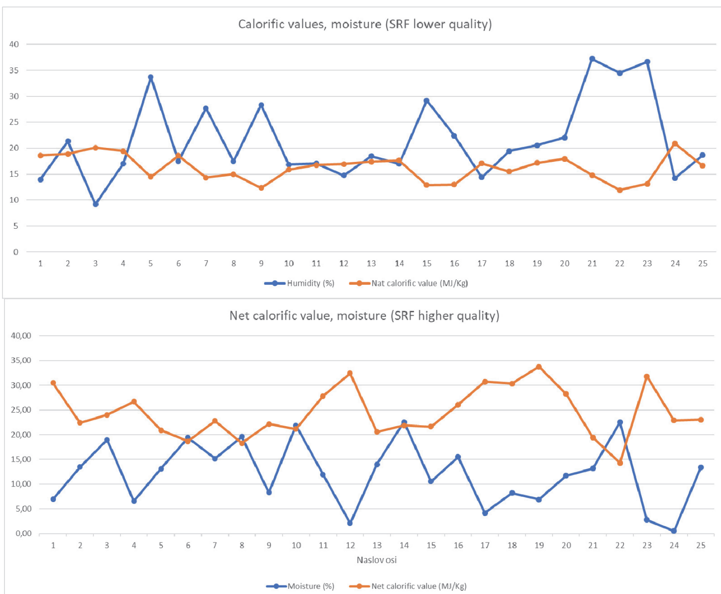

Figure 2: *Calorific values compared to the moisture content of individual fuel samples of lower quality (up) and higher quality (down)*

5.4 Results of thermogravimetric analysis and differential dynamic calorimetry

To facilitate the understanding of the behaviour of solid alternative fuels in heat treatment, we performed a laboratory analysis of the fractions that contribute the highest value of caloric energy to the fuel, namely plastics. We analysed four samples. The results of the analysis were compared with the research already conducted in this field. In the case of samples 1, 2 and 3, the measurement was carried out in the temperature range from 30 to 1000 °C with a temperature step of 20 K/min, in an inert nitrogen atmosphere, with a gas flow of 100 mL/min. In the case of sample four, the measurement was made in the range from 30 to 700 °C with a temperature step of 10 K/min, in an inert nitrogen atmosphere, with a gas flow of 100 mL/min.

Plastic polymers in waste are composed of synthetic or natural materials, chemical building blocks of monomers are placed in high molecular weight chains, and the main element is carbon. Other elements are oxygen, hydrogen, nitrogen and other inorganic and organic elements. Research has shown that the thermal decomposition of plastics takes place at elevated temperatures. In a study of the thermal analysis of alternative fuel components, *[9]*, it was found that plastics behave differently at elevated temperatures.

Sample 1, plastic bottle belongs to the group of PET or PETE plastics. Figure 3 (left) shows that the sample decomposes almost completely. Weight drops by 84.3% or 8.45 g. The initial or initial weight of the sample was 10.0260 mg. The sample began to decompose at a temperature of 434.20 °C and completely decomposed to a temperature of 497.94 °C, which is consistent with the results from *[9]*. The decomposition temperature, at which the mass drop is 50%, is 468.91 °C, determined by means of the 1st lead function (DTG-curve = differential thermogravimetry, differential thermal gravimetry – 1st lead of the thermogravimetric curve over time). Figure 3 (left) shows only one jump, which indicates that the decay takes place in one step, as also found in *[9]*. Figure 3 (right) shows the energy changes of sample 1, which has a starting weight of the sample was 6.34 mg. For substances that are partially crystalline, the melting point and the glass transition temperature can be determined. In our case, we see that the glass transition temperature is 81.99 °C and the melting point is 250 °C, with the enthalpy of melting, being released during the melting process, 271.68 mJ or 42.25 J/g.

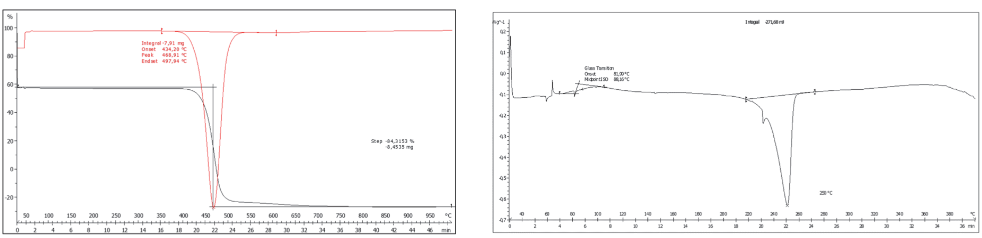

***Figure 3**: TGA analysis of sample 1 (left), DSC analysis (right)*

Sample 2, yogurt packaging, belongs to the PS plastic group. Figure 4 shows that the initial weight of the sample was 8.101 mg; the sample disintegrated almost completely, and the mass decreased by 7.8204 mg, representing 96.54%. The decomposition process started at a temperature of 359.85 °C and lasted until a temperature of 554.61 °C. Compared to the TGA analysis in *[9]*, depending on the composition of the crucible belonging to the PS group, the temperature change occurred earlier. We realized that for more accurate measurements, the exact chemical composition of individual plastics should also be determined, as these are very different from each other. The decomposition temperature, at which the mass has fallen by 50%, is 452.14 °C, determined by means of a DTG curve.

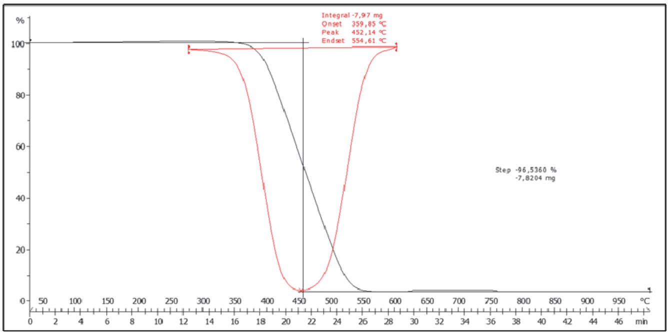

Figure 4*: TGA analysis of sample 2*

Sample 3, foil packaging, belongs to the group of PP plastics. Figure 5 (left) shows that the initial weight of the sample was 6.5010 mg; the sample completely disintegrated and the mass decreased by 99.39% and 6.46 mg, respectively. The sample decomposed in the temperature range from 437.06 °C to 534.36 °C. The DTG curve showed a 50 % drop in mass at 486.90 °C. Compared to the analysis [9], we can see that the degradation occurred at a higher temperature, which means that our sample is more resistant to temperature changes. Figure 5 (right) shows that the sample melted and that the melting point was 169 °C, which is much lower than in the case of sample 1. 410.39 mJ of energy was released in the melting process.

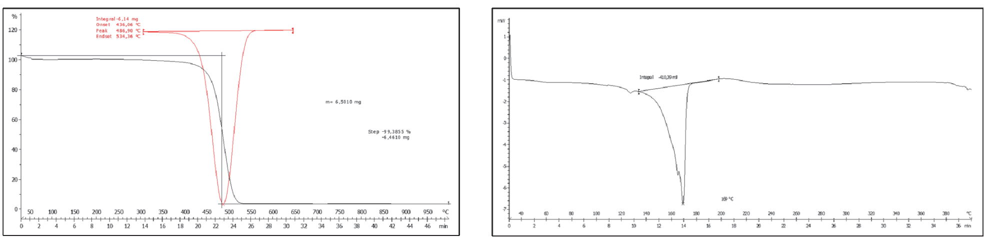

Figure 5*: TGA analysis of sample 3 (left), DSC analysis (right)*

Sample 4, shampoo packaging, belongs to the group of HDPE plastics. Figure 6 (left) shows that this sample also completely disintegrated. The initial weight of the sample was 17.8210 mg, and the final weight was 17.6890 mg, representing a 98.7 1% decrease. The sample began to decompose at 474.27 °C and completely decomposed at 525.36 °C. Compared to the study in *[9]*, the temperature range also differs slightly in this sample, but only by a few degrees; we can conclude that the results of the analysis are very similar. Figure 6 (right) shows that the initial weight of the sample was 11.7 mg, that this sample also melted and that the melting point was 133 °C, which is slightly lower than in the case of the Jamnica bottle and the flaxseed packaging. During the melting process, 1945.54 mJ of energy or 166.29 J/g was released.

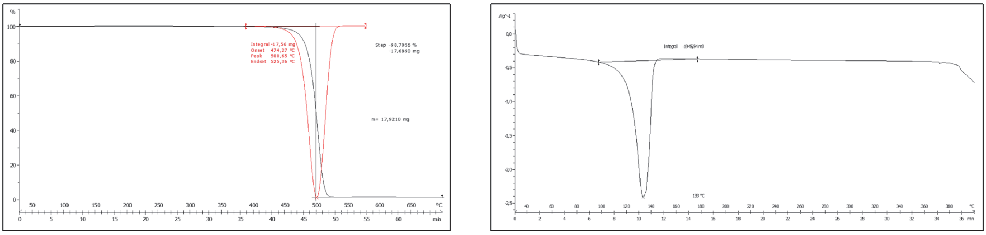

Figure 6: *TGA analysis of sample 4 (left), DSC analysis (right)*

If we compare the samples, we see that they differ slightly from each other in terms of temperature resistance. For sample 1 (PET), decomposition begins at 434.20 °C, the first temperature change of sample 2 (PS) is at 359.85 °C; for sample 3 (PP) the temperature change occurs at 437.06 °C, and sample 4 (HDPE) is the most heat-resistant - the change starts at 474.27 °C. It is true that all samples decompose within a given temperature range. Based on the results of the analysis, we can determine the order of durability of the considered plastics, from the least to the most durable: PS <PET <PP <HDPE. We found that our results were the same as in the comparative analysis *[9]*, in which they determined the same order of temperature resistance.

5.5 Calculation of energy value of containers

With the help of all the collected results, we also calculated the energy values of the container. After structural analysis, we determined the calorific values of individual fractions found in the literature and the calorific values obtained in the calorimetric analysis. For the calculation, we used the average values of the collected calorific values for the mass of 1 ton of alternative fuel.

The energy value was calculated using equation (5.1):

$$E_{odp} = \frac{NKV \times m}{3,6} \tag{5.1}$$

where:

- NKV – Net calorific value
- m – mass of fuel

The results of the calculation are presented in Table 8.

Table 8: *Calculation of energy value in samples used in research*

Analysed fuels	Calorific value [MJ/kg]	Mass [kg]	Calculation of energy value [kWh]
SRF of lower quality	16.29	1000	4.5
SRF of higher quality	24.50	1000	6.8
MP container	18.46	1000	5.1

According to the obtained average calorific values, the treated fuel of higher quality has the highest calorific value. The fractions analysed in the container's structural analysis also have a satisfactory calorific value and would probably represent a much larger share of the energy value after additional processing and potential enrichment with more caloric fractions.

6 CONCLUSION

Based on the results of structural analyses, we performed calorimetric analysis on fifty samples of SRF fuel and two samples of individual fractions that were most represented. The results were defined using classification tables and divided into quality classes. Due to the great influence of plastic, we performed thermal analysis. The results showed that the samples differed slightly in temperature resistance. It is true, however, that all samples decayed within a given temperature range. Based on the results of the analysis, we can determine the order of durability of the analysed plastics, from the least to the most durable: PS <PET <PP <HDPE. We found that our results are comparable to the results from the literature, and we can conclude that the performance of the experiments was of high quality. With the help of all the previously mentioned methods, we conclusively determined the energy value of our samples. The fractions analysed in the structural analysis of the container had a satisfactory calorific value compared to the treated SRF fuel. However, after additional processing and potential enrichment with more caloric fractions, they would probably represent a much higher share of energy value. Summarizing the entire research, we realised that waste represents both energy and user value. Better public awareness could make it easier to present the purposes of waste heat treatment and reuse.

7 Acknowledgements

We would like to thank Kostak d.d. for enabling calorimetric analysis of samples in the laboratory of the company's Waste Management Center. Thanks are also due to the Faculty of Chemistry and Chemical Engineering, University of Maribor, where we performed two thermal analyses of the samples, thermogravimetric analysis (TGA) and dynamic differential calorimetry (DSC).

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Nomenclature

(Symbols)	(Symbol meaning)
MSW	Municipal Solid Waste
MP	Mixed Packaging
SRF	Solid Recovered Fuel
MJ	Megajoule
kWh	Kilowatt hour
Kg	Kilogram
PET or PETE	Polyethylene terephthalate
HDPE	High density polyethylene
LDPE	Low density polyethylene
PVC	Polyvinyl chloride
PP	Polypropylene
PS	Polystyrene
TGA	Thermogravimetric analysis
DSC	Dynamic differential calorimetry
SPI	Resin Identification Code
MJ/kg	Megajoule/kilogram
mm	Milimeter
w%	Ash content
°C	Degree Celsius
Fe	Iron
CO	Carbon monoxide

g/cm^3	Gram/cubic centimeter
ρ	density
Eodp	Energy of waste
NKV	Net calorific value

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ANALYSIS AND EFFICIENCY OF A GADOLINIUM MAGNETOCALORIC MATERIAL PLATE

ANALIZA IN UČINKOVITOST GADOLINIJSKE MAGNETOKALORIČNE PLOŠČE

Botoc Dorin [ℜ,1], Rusu Ionut-Bogdan[1], Plesca Adrian[1], Avsec Jurij[2]

Keywords: Gadolinium Plate, magnetocaloric effect, magnetic flow, energetic efficiency

Abstract

In this article, the influence of a controlled magnetic field on gadolinium plates was modelled and simulated to be used in magnetic refrigeration installations. This is a state-of-the-art technology that does not use refrigerants and does not work based on vapour compression, which is based on the operation of the magnetocaloric properties of the material used; in the case below, this material, in the form of a flat plate, has certain magnetocaloric properties and under the influence of magnetic induction can be used successfully in such innovative installations. The advantages of using gadolinium in the form of a flat plate in a magnetic regenerator and thermal energy dissipation on its surface under the controlled magnetic field's influence were studied.

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Povzetek

V tem članku je bil izdelan model in simuliran vpliv nadzorovanega magnetnega polja na gadolinijeve plošče za uporabo v magnetnih hladilnih napravah. To je najsodobnejša tehnologija, ki ne uporablja hladilnih sredstev in ne deluje na osnovi kompresije hlapov. Tehnologija temelji na delovanju magnetokaloričnih lastnosti uporabljenega materiala; v spodnjem primeru ima ta material v obliki ravne plošče določene magnetokalorične lastnosti in se pod vplivom magnetne indukcije lahko uspešno uporablja v inovativnih instalacijah. Proučene so bile prednosti uporabe gadolinija v obliki ravne plošče v magnetnem regeneratorju in odvajanja toplotne energije na njegovi površini pod vplivom nadzorovanega magnetnega polja.

1 INTRODUCTION

Magnetic refrigeration is a new technology that uses the magneto-caloric effect developed in the solid-state to produce a refrigeration effect, [1]. Modern society is highly dependent on reliable refrigeration technology. Without it, the food supply would be seasonal and limited to local, non-perishable products. and comfortable living conditions would not be possible. Furthermore, many medical advances, for example, MRI, organ transplantation, tissue and organ cryogenics and cryosurgery, would be impossible. Surprisingly, all these and other developments in obtaining and maintaining temperatures below ambient temperature are supported by technology that remains essentially unchanged since it was invented more than a century ago. Refrigeration close to room temperature is based entirely on a vapour-compression refrigeration cycle. Over the years, all parts of a commercial refrigerator (i.e., the compressor, the heat exchangers, the refrigerant and the packaging) have been improved due to the extensive research and development efforts carried out by academia and industry. However, both recent and anticipated improvements in technology are on the rise, as refrigeration is already close to the fundamental limit of energy efficiency.

Furthermore, chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), and other chemicals used as refrigerants are hazardous to the environment and cause ozone depletion and global warming; therefore, vapour compression refrigeration contributes significantly to the impact of the environment in which we live. Refrigeration is defined as the use of a mechanism that changes its temperature in response to certain thermodynamic transformations to cool an object or an environment. These variations must be made quickly and repeatedly, reversibly, and with minimal energy losses. Both the heating and cooling of soft ferromagnetic materials in response to the increase and decrease of the magnetic fields have been known since the second half of the 19th century, when Warburg (1881) reported a small but measurable temperature change in pure iron in response to the changes in the magnetic field. Today, this phenomenon is known as the Magnetocaloric Effect (MCE) and the materials that show large, reversible changes in temporary temperature in response to changing magnetic fields are usually called magnetocaloric materials.

Magnetic refrigeration that uses solid materials such as gadolinium (Gd) as a refrigerant illustrates the MCE, where there is an increase or decrease in temperature when magnetized and/or demagnetized, respectively. Recently, materials have been developed in which there are sufficient changes in temperature and entropy, which makes them useful for applications at high temperatures. Effective and current solutions for reducing energy consumption using magnetic materials include the use of permanent magnets as sources of magnetic fields in electrical systems and materials with MCE in magnetic refrigeration systems at room temperature. These systems' energy efficiency is closely linked to the proper choice of the magnetic materials involved according to the targeted performance requirements and the technological implementation solutions at acceptable cost prices.

Magnetic materials are a class of materials that are characterized by magnetization states with useful functions. The phrase "state of magnetization" means that the state of matter characterized by magnetic moment of the unit of volume other than zero.

It is atomic in nature, being generated by the movement of electrons in orbit and around its own axis; these movements give rise to magnetic moments. The magnetization state of a magnetic material can be temporary, when it depends on the existence of an external magnetic field and cancels with it, or permanent, when it is independent of the existence of an external magnetic field.

2 LITERATURE REVIEW

There are many scientific articles, patents, and books in which researchers have highlighted the benefits of using magnetocaloric materials for refrigeration processes, and the potential of such materials has been demonstrated as an effective material for saving energy. Gao et al. explained in detail the transformation of magnetocaloric energy from materials, where the relevant disadvantages were also explained, *[2].*

In both Europe and the US, a huge amount of energy could be saved from conventional refrigeration and air conditioning by approaching magnetic refrigeration.

The main reason for the increased interest in magnetic refrigeration is its ecological operation, extreme energy efficiency and the complete removal of refrigerants harmful to the ozone layer and the environment, *[3].*

The research leads to the development of the refrigeration equipment that can operate at room temperature. There have been various successful attempts at the prototype or experimental levels, such as products developed by General Electric and Haier.

The properties that can be used in refrigeration installations are due to the extraordinary response of these materials to external magnetic fields; the exposure of such properties takes place close to Curie temperature (i.e., the temperature at which the self-possessed basic magnetic properties decrease and the material temperature depends by applying the magnetic field), *[4].*

The magnetocaloric effect has been used since 1920 to examine the magnetic structure and properties of iron and other related elements of various materials, *[5].*

Research tends to develop important developments and highlight the exponential progress that led to Toady's knowledge and understanding of the magnetocaloric effect. Faraday discovered that the variation in magnetic flux over time results in the induction of electric currents, *[6].* Joule explained the idea related to electric currents and associated thermal energy, stating that the thermal energy released due to the induced magnetic induction is equivalent to the thermal energy produced, and the rapid magnetization and demagnetization can lead to the heating of the magnetocaloric material due to applied thermal energy, *[7].*

3 MODELLING BOUNDARIES

The modelling and simulation of processes for gadolinium (Gd) plates were performed in COMSOL Multiphysics software. The 3D model was drawn in the "mesh geometry" tab of the Comsol software, and the symmetry is shown in Fig.1.

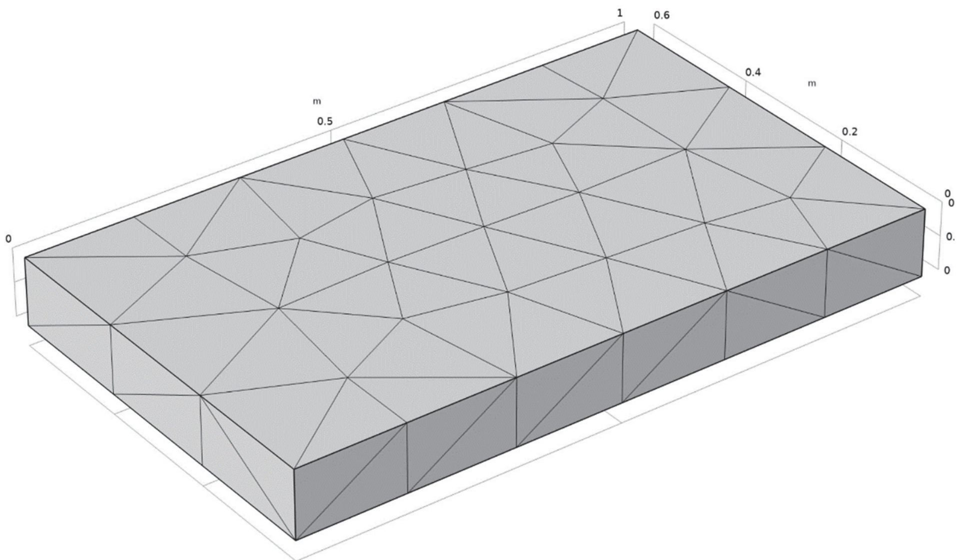

Figure 1*: Comsol 3D mesh plan for Gd plate*

The length of the plate is 100 cm, while the height is 10 cm, and the width is 60 cm. The table below shows the full dimensions of the model.

Table 1: *Gd plate dimensions*

Name	Expression	Value
L(length)	100[cm]	1 m
B(height)	10[cm]	0.1 m
W(width)	60[cm]	0.6 m

The physics selected for the simulation is the main determinant of the solution and the boundary conditions. The models that were used in the simulation are magnetic fields, heat transfer in solid materials, and laminar flow for fluid solvers, *[8].*

All these coupled found the numerical solution of the problem of the magnetocaloric effect of the Gd plate, which can be used successfully in magnetic regenerators.

The magnetocaloric effect in the COMSOL Multiphysics, model was introduced using an interpolation function of the thermophysical data.

$$M, C_p, \Delta T_{ad} = f(T, \mu_0, H(t))$$

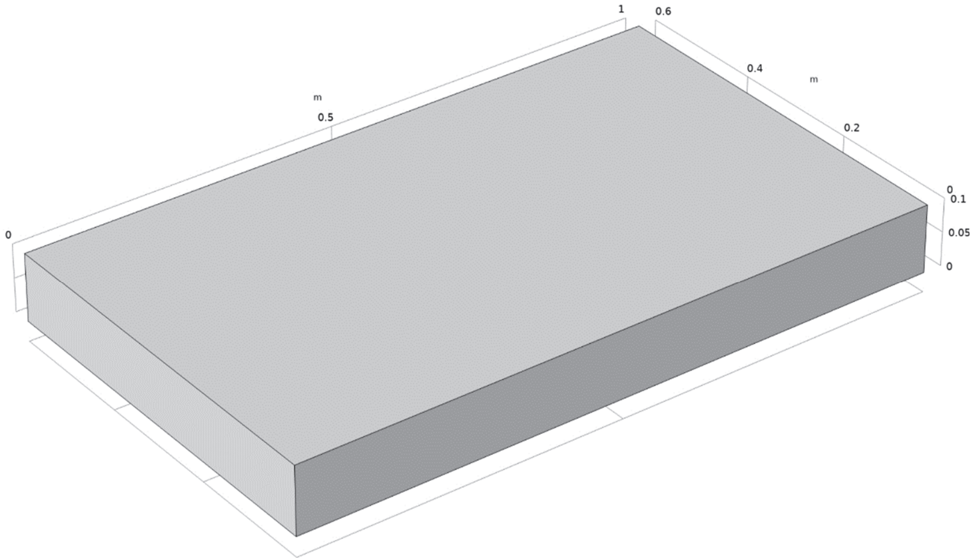

***Figure 2**: Gd board model. 3D*

4 RESULTS

Figure 3 shows the temperature profile on the surface of the Gd plate; the temperature begins to dissipate slowly due to the effects of thermal convection.

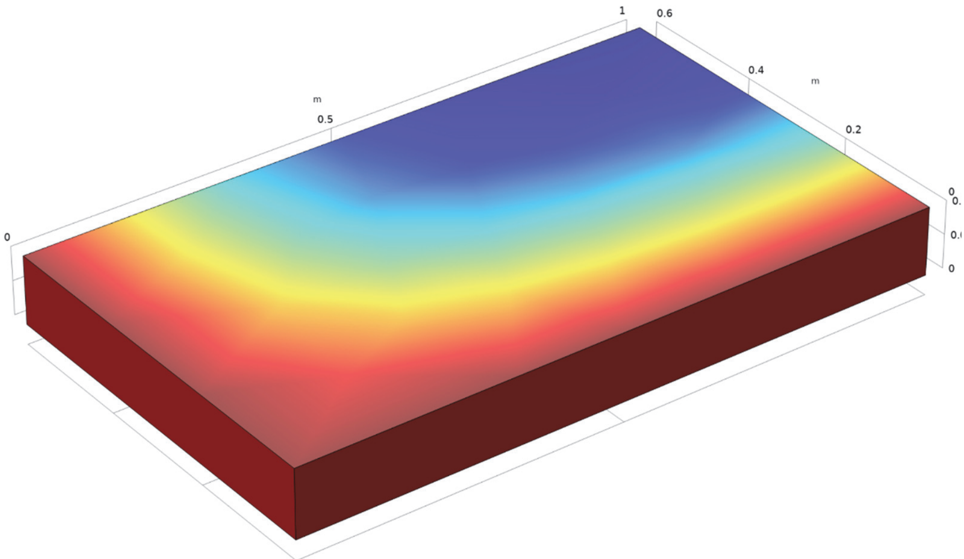

Figure 3: *Gd board temperature profile. 3D modelled in COMSOL*

The decrease in temperature due to the decrease in the magnetocaloric effect is similar to the reports made in research journals, *[9].* Successful simulations were performed using the COMSOL model, and the transient model can be adopted for another approach. The chosen material (Gd) is widely used in research in the field of magnetocaloric materials, *[10-13].*

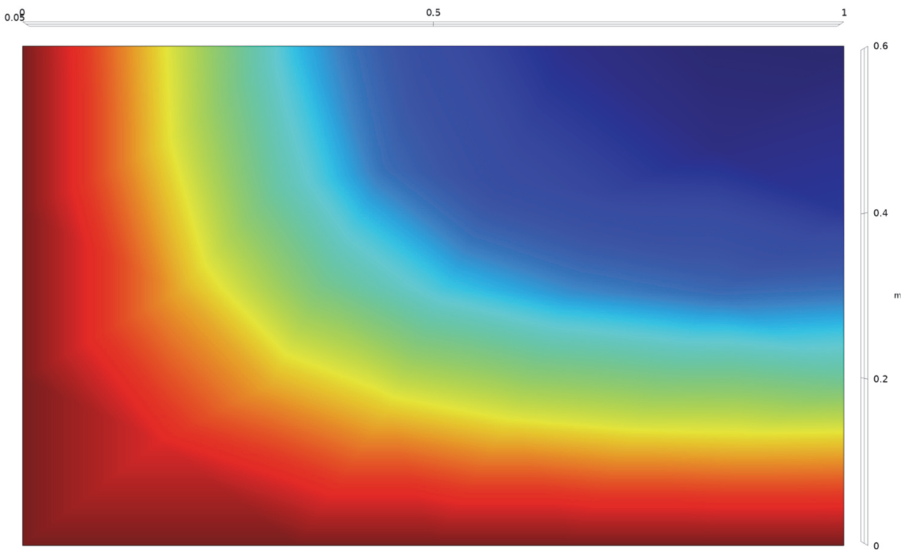

Figure 4: *The temperature profile of the Gd plate. on the xy*

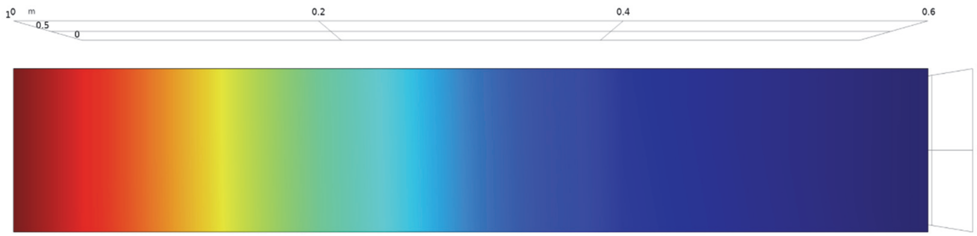

Figure 5: *The temperature profile of the Gd plate. on the yz*

Table 2: *The properties mostly used for gadolinium*

Tangent coefficient of thermal expansion	1/K	Thermal expansion
Isotropic tangent coefficient of thermal expansion	1/K	Thermal expansion
Thermal conductivity	W/(m·K)	Basic
Heat capacity at constant pressure	J/(kg·K)	Basic
Density	kg/m^3	Basic
Resistivity	Ω·m	Basic
Coefficient of thermal expansion	1/K	Basic
Electrical conductivity	S/m	Basic
Local property HC	J/(mol·K)	Local properties
Local property VP	Pa	Local properties
Local property TD	m^2/s	Local properties

The model selected for simulation and modelling is a determining factor of the solution and the limit.

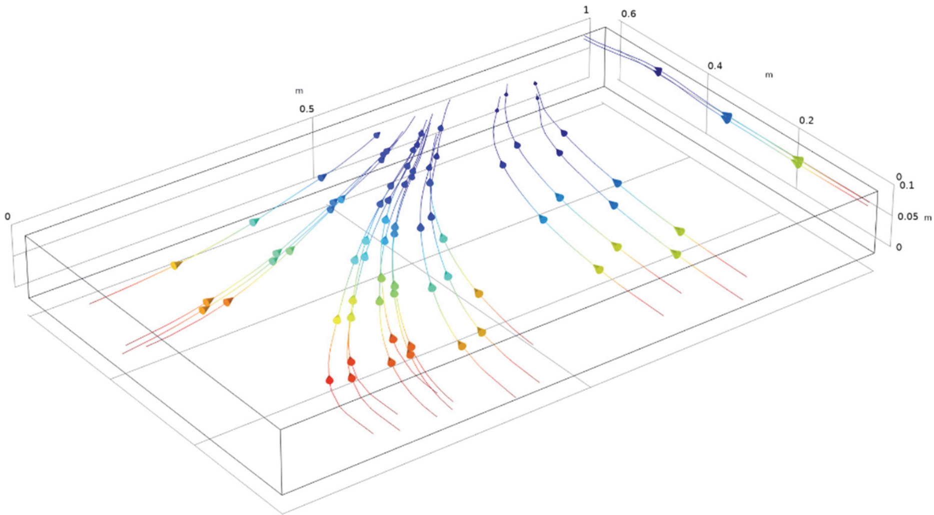

Figure 6: *Gd plate temperature flow profile in 3D*

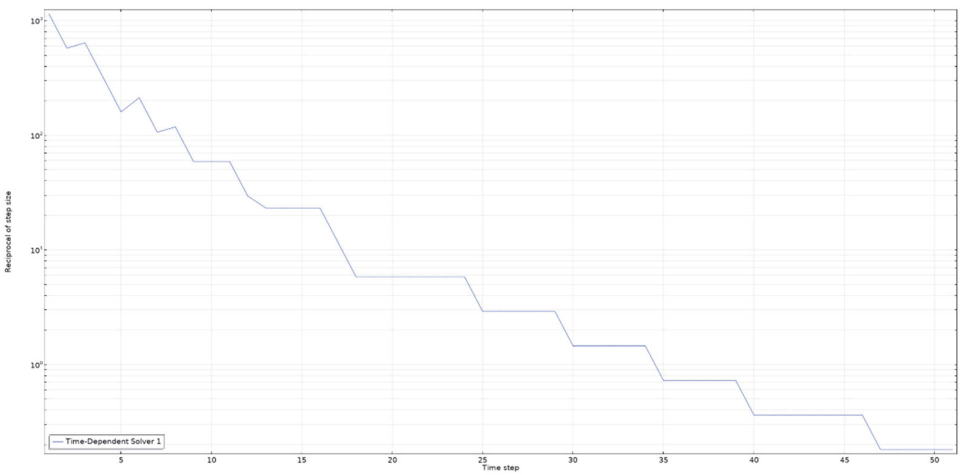

Figure 7: *The evolution of the temperature flow and the dispersion in time on the surface of the Gd plate*

Figure 6 presents the evolution of the temperature variation on the whole surface of the Gd plate, inside the magnetic regenerator (AMR) and for about 50 minutes.

5 CONCLUSION

In this article, the modelling and simulation of the Gadolinium board were performed in COMSOL Multiphysics software. The study of this material focused on the dissipation of heat flow on the integral surface of the material, the properties of the material and the orientation of the dipole moments. The research provides important perspectives on this field and is based primarily on magnetocaloric testing in magnetization conditions with directions for further development in the development of prototypes and magnetic installations. This study requires the understanding and knowledge of the thermodynamic principles of operation of magnetocaloric refrigeration installations. The simulation began with the magnetization of the Gd board, using the limit condition of Ampere's law, which is governed by the modulus of the magnetic field.

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COST-BENEFIT ANALYSIS OF FROST PROTECTION METHODS

ANALIZA STROŠKOV IN KORISTI METOD ZA ZAŠČITO PROTI POZEBI

Matej Fike[ℜ], Mateja Fekonja[1], Miha Smrekar[2]

Keywords: Spring Frost, Frost Protection, Cost-benefit analysis, NPV

Abstract

Agricultural losses due to frost are high in various parts of the world, and in Slovenia, frost damage has frequently occurred in recent decades. Multiple methods for preventing frost damage exist and have been researched more or less extensively. Despite this, frost prevention measures are relatively sparsely used in Slovenia. This article aimed to review and compare active frost prevention technology for a case study of a typical fruit farm in Slovenia, based on a cost-benefit analysis. Most of the active methods require either large capital investment or have a high annual cost. According to our analysis, burning wood, used in Slovenia to battle frost damage in orchards and vineyards, proved to be the most cost-effective method, which is probably why it remains in wide use.

Povzetek

Izgube kmetijskih pridelkov zaradi pozebe so velike po vsem svetu, v Sloveniji pa se škoda zaradi pozebe v zadnjih desetletjih pojavlja vse pogosteje. Znanih je veliko metod za preprečevanje škode zaradi pozebe, ki so že bolj ali manj raziskane. Kljub temu pa se ukrepi za preprečevanje škode v Sloveniji zelo redko uporabljajo. Cilj tega članka je bil izdelati pregled in primerjavo različnih aktivnih ukrepov proti pozebi, ki so primerni za tipično sadjarsko kmetijo v Sloveniji na podlagi analize stroškov in koristi. Ugotovili smo, da so aktivni ukrepi dobra naložba, če so uporabljeni. Večina aktivnih ukrepov zahteva

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ali visok začetni kapital ali pa imajo velike letne stroške. Kurjenje, ki ga v Sloveniji uporabljajo za boj proti pozebi v sadovnjakih in vinogradih, se je po naši analizi izkazalo kot najbolj stroškovno učinkovita metoda, kar je verjetno razlog, da je še vedno v široki uporabi.

1 INTRODUCTION

Among other weather-related phenomena, frost damage is responsible for serious agriculture production losses. The Food and Agriculture Organization of the United Nations reports that more economic losses have been caused by the freezing of crops in the USA than by any other weather hazard, *[1].* In Slovenia, the frequency of spring frost was higher in recent decades than previously recorded, *[2]*.

Fields and orchards can be protected from the frost by passive and active methods. Passive techniques cannot completely prevent frost damage, but it is very important to implement them because they make it easier and more efficient to implement active methods, *[3].*

This study aimed to make a cost-benefit analysis and comparison of active frost prevention technology for a case study of a typical fruit farm in Slovenia. For this study, we assumed that all analysed active protection methods have the same effectiveness and have compared the investment value of specific methods, based on the defined criteria. We also analysed the cost-benefit of wood-burning, which is commonly used in Slovenia to prevent frost damage to vineyards and orchards.

2 DATA AND METHODS

2.1 Net present value

A thorough financial analysis should be conducted before investing in frost protection. A sound investment should satisfy three criteria: it must be profitable, the cash flow must be financially feasible, and the risk must be compatible with the preferences and financial position of the investor. Economic analysis of frost protection is complicated by the nature of weather and the net benefits derived from adopting a particular frost protection technology. One may not be able to evaluate the financial risk of the adoption decision unless adequate (e.g., 20- to 50-year time series) minimum and maximum temperature data are available, *[1]*.

As discussed in the introduction, there are different ways to protect crops against frost damage. We focused on solid fuel heaters, liquid fuel heaters, sprinklers, wind machines, helicopter rental, and wood burning in the analysis. We decided to create an analysis of the Net Present Value (NPV) for each protection method. With NPV, a project is measured according to its value rather than its costs. NPV assumes that money today is worth more than an equal amount of money tomorrow. Since the calculation is based on forecasted cash flows, a risk exists that the planned cash flows will not be reached, and thus must be considered, *[4].*

We took each specific protection measure, made an analysis of the major cost factors, and divided the costs into acquisition costs and variable costs, which can depend either on the frost frequency or on the total frost duration. The energy requirement for protecting the orchard E_R was set to be $140\ W\ m^{-2}$.

2.2 Solid fuel heaters and burning wood analysis

Orchard heaters are commonly used to prevent frost damage to fruit and fruit trees. Multiple types exist: pipeline, lazy flame, return stack, cone, solid fuel and liquid fuel. Solid fuel heaters usually only consist of solid briquettes, which are placed on the ground and ignited. Proper location of the heaters is essential for the uniformity of the radiant heat distributed among the trees [5]. The number of heaters required per hectare N can be calculated using the following formulation from *[1]*:

$$N = \frac{E_R}{E_O F_C}(3.6 \cdot 10^7) = 503\,\frac{heaters}{ha} \tag{2.1}$$

where N is the number of heaters required per unit of orchard area, E_R is the energy requirement $[W\ m^{-2}]$, E_O the energy output per heater $[MJ\ kg^{-1}]$, F_C is the fuel consumption per heater per hour $[kg\ h^{-1}]$. In our case, we used the following values: $E_O = 33.4\ MJ\ kg^{-1}$, $F_c = 0.3\ kg\ h^{-1}$. If we assume that $1\ kg$ of solid fuel costs $p\ =\ €4.45/kg$, and that every heater has a mass of $M_U = 2.5\ kg$, we can calculate the total price of solid fuel heaters per hectare per hour using:

$$P = \frac{p \cdot F_C \cdot N}{M_U} \cong 270\,\frac{€}{h} \tag{2.2}$$

We also took into account the acquisition costs of equipment related to solid fuel heaters, namely an ignition torch, a frost alarm, a minimum thermometer, with a total cost of $€240$, and an approximate surveillance manhour cost, which was approximated at $€10/h/person$ with four people controlling the fires. The total variable cost per hour is $€310/ha/h$. Additional costs are the labour costs of placing, starting, and stopping the fires, removal of waste, lighting torch fuel, etc., which were approximated to be $€70/ha$ per every frost event.

For comparison, we calculated the same parameters for another solid fuel type, wood, which is commonly used to minimize frost effects in Slovenia. In this case, we assumed that $E_O = 16\ MJ\ kg^{-1}$, $F_C = 5\ kg\ h^{-1}$. Based on the energy requirement, we calculated that we would need 63 bonfires per hectare, each weighing $M_U = 10\ kg$. We assumed that the wood price is $€60/m^3$, which, calculated with an average mass density of $470\ kg/m^3$, gives us a price of $€0.1277/kg$. This gives us, together with surveillance costs, a total variable cost of approximately $€52/ha/h$. Variable costs, including manhour labour to set up the fires, fuel for trucks, etc., were estimated to be around $€200/ha$ per event.

2.3 Liquid fuel heater analysis

Liquid fuel heaters typically burn up to 4 litres of fuel per hour. The maximum heating effect for a well-adjusted stand-alone heating system in the right environment is about 300 to 330 $W\ m^{-2}$ [6]. In our case study, we took into consideration liquid fuel heaters with the following data: Energy output $E_O = 38\ MJ\ l^{-1}$, fuel consumption $F_C = 1.4\ l\ h^{-1}$. That gives us a total number of heaters per hectare of:

$$N = \frac{E_R}{E_O F_C}(3.6 \cdot 10^7) = 98\,\frac{heaters}{ha} \qquad (2.3)$$

Liquid fuel is typically burnt in some type of a metal container with an opening at the top. Among the initial capital costs required to invest in a liquid fuel heating system are the cost of heaters themselves, a fuel can, a fuel pump, a reserve tank, ignition torches, a frost alarm and a minimum thermometer. Altogether, we estimated the initial capital costs of the equipment to be €5,000. Variable costs per hectare include labour costs for starting and stopping the fires, refilling the heaters, and fuel for torches. Variable costs per hectare per frosting event were estimated to be €$28/ha$. The total cost of fuel and labour of surveillance per hour was calculated to be €$58/ha/h$.

2.4 Sprinkler analysis

Sprinklers can be used to provide sufficient heat to plants in an environment with little wind and appropriate temperatures, as long as a film of free-liquid water surrounds the fruit leaf. The required application can be estimated if heat loss by convection, radiation and evaporation is known, *[7]*. Among the initial capital costs are the main and secondary flow lines, tubing accessories, sprinkler heads, regulators, and trenching costs, the cost of the pumping plant, installation of the system, alarms and thermometers. Altogether, the equipment cost estimation was €$7{,}450/ha$. Variable costs per hectare per frosting event, which included only the starting and stopping manhour labour, were valued at €$11/ha$, while the variable costs per hour of protection were presumed to be €$24/h$.

2.5 Wind machine analysis

Wind machines are tall, fixed-in-place, engine-driven fans that pull warm air down from high above ground during temperature inversions, and raise air temperatures in an orchard. They are not meant to be operated in windy conditions because high wind forces might cause too much stress on their blades, *[8]*. They are usually powered by internal combustion engines, although electrically powered fans can be used as well. Each wind machine, typically rated at $100\ kW$, is able to protect an area of around 4-5 hectares. In our analysis, a wind machine with an internal combustion engine was considered. The total acquisition costs of a single unit were estimated to be €35,000. Variable costs per single event per hectare, which include maintenance labour, vehicle use, and other miscellaneous replacement parts totalled €$320.40/ha$ per event. Variable costs per hour of protection, which include fan fuel cost and surveillance labour manhours were calculated at €$19/h$.

2.6 Helicopter analysis

Helicopters have proven to be an effective method of crop protection. Bates, *[9]*, for example, found the helicopter action could raise the crop temperature above the plant's frost danger point. The affected area radius is approximately $r = 30\,m$, and 15- to 20-minute passes over the orchard are needed, *[9]*. We assumed in our case, that the investor will not buy a helicopter, but will rent one when needed. In this case, the only variable cost is helicopter and pilot rental per hour, which was estimated to be €1000 per hour. If we take into account an average helicopter speed of $15\,mph$ ($v = 6.7\,m/s$), and the required pass-by time $t = 15\,min$, we can approximately calculate the maximum area a single helicopter can cover within the given time span, given the width $w = 2r = 60\,m$, that denotes the affected span of each pass by:

$$A_{max} = vtw = 6.7\frac{m}{s} \cdot 15\,min \cdot 60 \cdot \frac{s}{min} \cdot 60\,m = 316{,}800\,m^2 = 31.68\,ha \quad (2.4)$$

2.7 Case study definition

Our case study orchard farm is located in Slovenia. Based on model calculations made by the Agricultural Institute of Slovenia, available in *[10]*, we estimated some typical values for a farm in Slovenia. Our chosen orchard area is 5 hectares. Annual fruit production mass is $40\,tonnes\ per\ hectare$. The selling price of apples is €$0.49\ /kg$, and the production costs add up to a total of €$17{,}423\ /ha$. Based on available and gathered data, we estimated that one major frost event happens every two years, and the length of the frost is approximately 8 hours. During the frost events, damage occurs to the plants, affecting 50% of the fruit. The complete input parameters for our analysis can be seen in Table 1 and Table 2.

Table 1: *Input parameters to the cost-benefit analysis*

Input parameters	
Orchard area	5 ha
Fruit mass	40 t/ha
Crop price	€0.49/kg
Production costs	€17,423 /ha
Frosty year occurrence (x years)	2 years
Number of frosts per frosty year	1 / year
Length of every frost event	8 h
Crop survival ratio	50 %
Discount rate	4.00 %
Project lifetime (years)	6 years
Annual results, without frost	
Income per hectare	€19,640/ha
Costs per hectare	€17,423/ha
Profit per hectare	€2,217/ha
Total profit	€11,087
Annual results, with frost	
Income per hectare	€9,820/ha
Costs per hectare	€17,423/ha
Profit per hectare	-€7,603/ha
Potential income per hectare	€9,820/ha

Table 2: *Annual cost and investment data for each protection method*

Protection method	Annual cost	Investment
Solid fuel heaters	€12,750	€1,200
Liquid fuel heaters	€2,460	€25,000
Sprinklers	€1,015	€37,250
Wind machines	€2,362	€35,000
Helicopters	€8,000	/
Wood burning	€4,680	€1,200

The net present value (NPV) method requires three parameters for each period for which we wish to calculate the current investment value; the annual cash flow, the discount rate and the expected lifetime of the project, in which we want to yield positive results, minus the initial investment cost. The NPV formula can be written as:

$$NPV = \sum_{i=1}^{n} \frac{R_i}{(1+r)^i} - Initial\ investment \tag{2.5}$$

where R_i is the estimated net cash flow for i-th period, r is the discount rate, and n is the life of the project.

The initial investment in our case are all the costs of any equipment that have to be made before the first frost event occurs: the total equipment acquisition costs. We have chosen the net cash flow R_i to be the potential savings from protection, if a protection measure was to be installed or chosen to be used for protecting the crops. The effectiveness of all of the above measures was set to be 100 % to ensure the most optimal economic outcome in the case of investing. The results of the cost-benefit analysis can be seen in Table 3 and Figure 1. Our project lifetime is $n = 6\ years$.

3 RESULTS

Our economic analysis shows, as seen in Table 3, that all methods of protection yield effective results in the given project lifetime. Sprinklers, wind machines, and liquid fuel heaters require a large capital investment and have lower variable costs, while solid fuel heaters, helicopters and wood-burning require little to no capital investment, but have more significant variable costs. The most cost-effective method, according to our calculation, was burning wood, as it has the largest net present value of €105,003.64 after the designated project lifetime. The cost of all of the methods without frost events was considered to be zero, as little to no maintenance was considered to be required for the appropriate installed systems due to the short project lifetime.

Table 3: *Net present value of different active protection methods*

Protection method	Annual cash flow (with frost)	Annual cash flow (no frost)	NPV (6 years)
Solid fuel heaters	€36,350	€0,00	€61,870.10
Liquid fuel heaters	€46,640	€0,00	€93,069.37
Sprinklers	€48,085	€0,00	€88,542.78
Wind machines	€46,738	€0,00	€83,593.17
Helicopters	€41,100	€0,00	€88,458.49
Wood burning	€44,420	€0,00	€105,003.64

Below, in Figure 1, the NPV of the protection methods is shown. It is clear that most of the protection methods give positive cost-benefit results (in this case, the NPV value is greater than zero for all analysed protection methods in just one year) after the initial capital investment, if calculating using the specified input data.

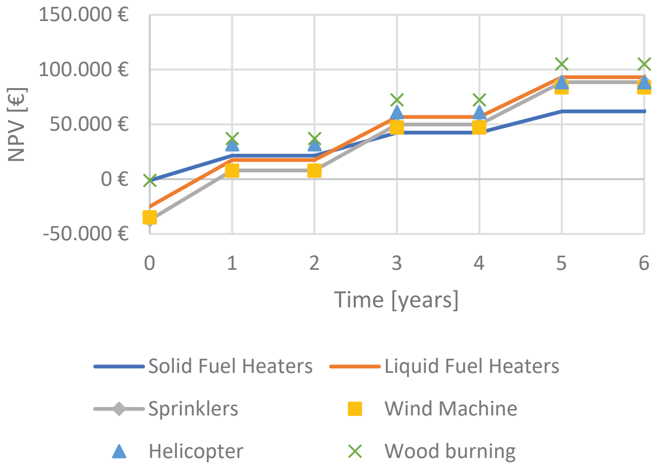

Figure 1: *Net Present Value of various active frost protection methods*

In Figure 2, we directly compare the total annual costs per hectare for our case study farm to illustrate the comparative cost of each protection method. Based on our calculation, a minimum of $€203/ha$ of variable costs are needed to ensure sprinkler frost damage protection. Most methods have an annual variable cost range of approximately $€200/ha$ to $€1600/ha$.

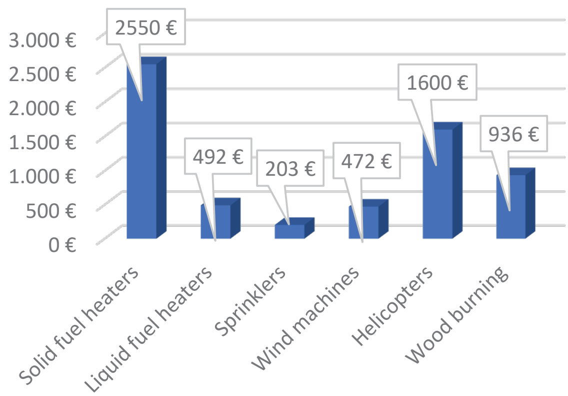

Figure 2: *Annual variable costs of various protection methods per protected hectare per frosty year*

The total investment costs per hectare are shown in Figure 3. Initial capital costs for renting a helicopter, wood-burning and solid fuel heaters are low while liquid fuel heaters, sprinklers and wind machines investment cost are high.

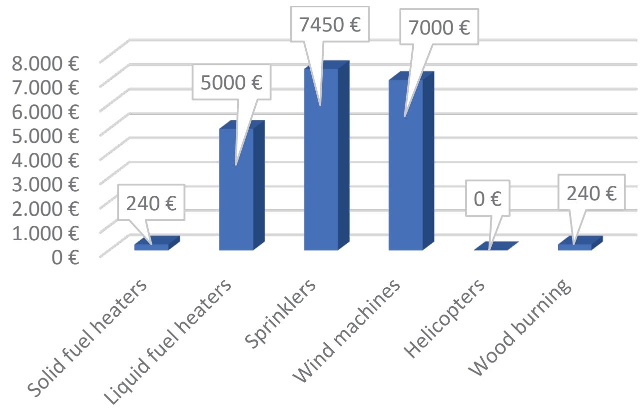

Figure 3: *Investment costs of various protection methods per hectare*

4 CONCLUSION

Based on the conducted cost-benefit analysis, it is evident that frost protection systems, when effective, are beneficial in increasing the total profit of fruit producers, in an environment where frost is a relatively frequent occurrence. In our case study, all of the methods yielded positive economic results as soon as the first frosty year.

The most effective measure was burning wood, which increased the potential profit (over the project lifetime of six years) by more than €100,000 in total. Sprinklers and liquid fuel heaters were approximately equally economically successful. Wind machines, helicopters, and solid fuel heaters have the smallest benefit-to-cost ratio, but these investments also gave positive investment value and are to be considered for potentially decreasing damage due to frost.

Figure 4: *Example of burning wood in Slovenia*

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Nomenclature

(Symbols)	(Symbol meaning)
t	time
N	heater count per hectare
E_R	frost protection energy requirement
E_O	frost protection energy output
F_C	fuel consumption
p	fuel price
P	heater price
M_U	heater mass
w	helicopter affected protection width
v	speed
A	area
NPV	Net Present Value
R_i	net cash flow
i	annual period
r	required rate of return

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

PROIZVODNJA UMETNEGA HLADU, OSNOVANA NA MAGNETNOKALORIČNEM UČINKU

Botoc Dorin[1],ℜ , Rusu Ionut-Bogdan[1], Plesca Adrian[1], Avsec Jurij[2]

Keywords: Energy efficiency, magnetocaloric material, magnetic refrigeration, active magnetic regenerator

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).

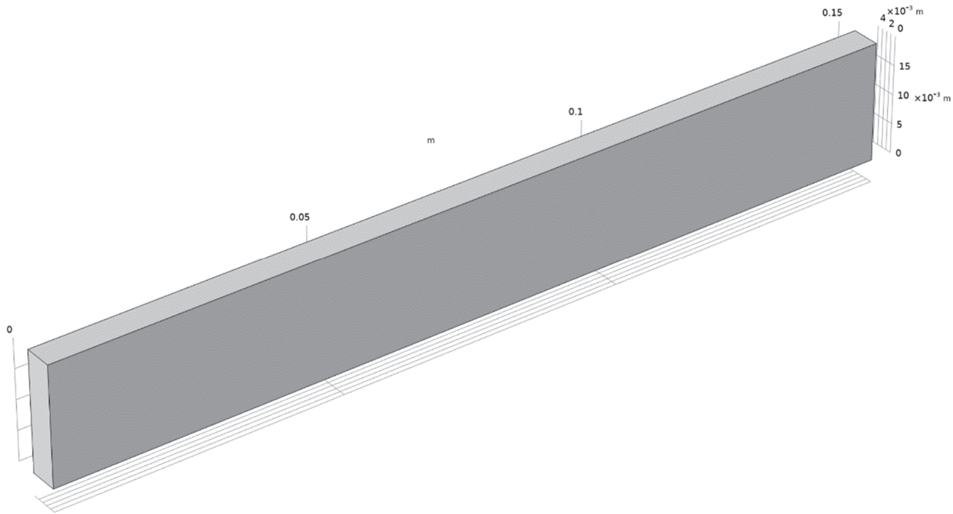

Figure 1: *COMSOL Multiphysics 3D model for simulation*

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.

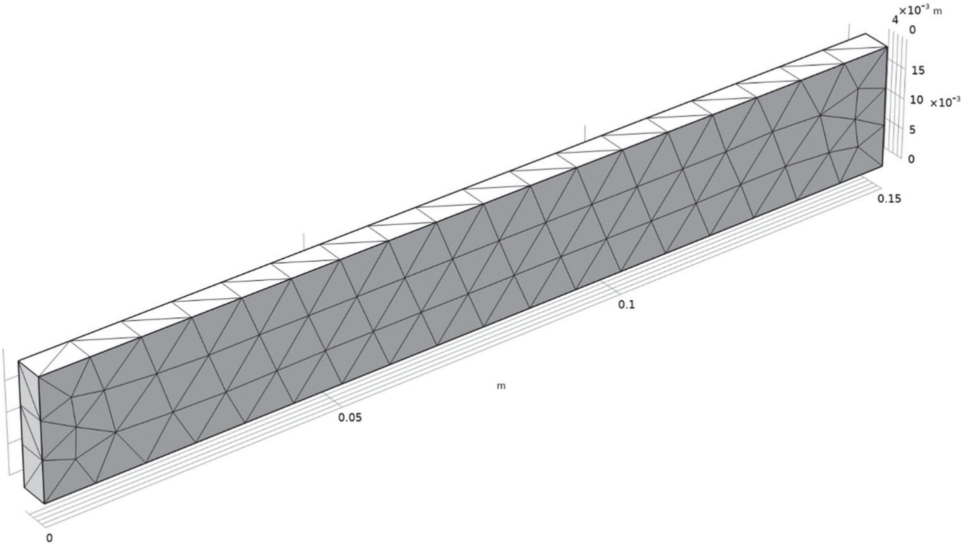

Figure 2: *3D MESH model, used for simulation*

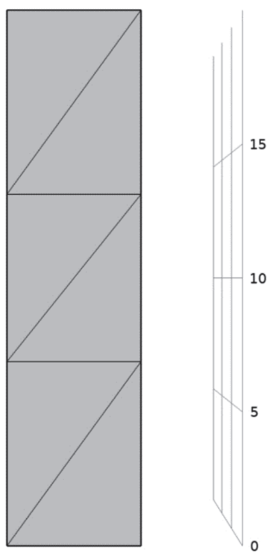

Figure 3: *MESH model on the yz axes*

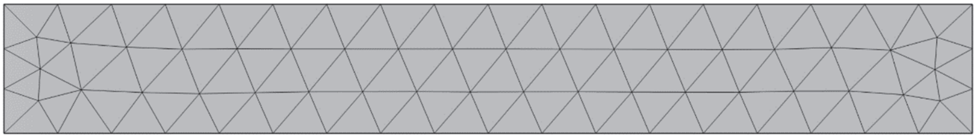

Figure 4: *MESH model on the xz axis*

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).

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

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

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

Mechanical work:

$$\mathrm{dw} = -\mu_0 \mathrm{HdM} \quad (4.3)$$

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

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

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.

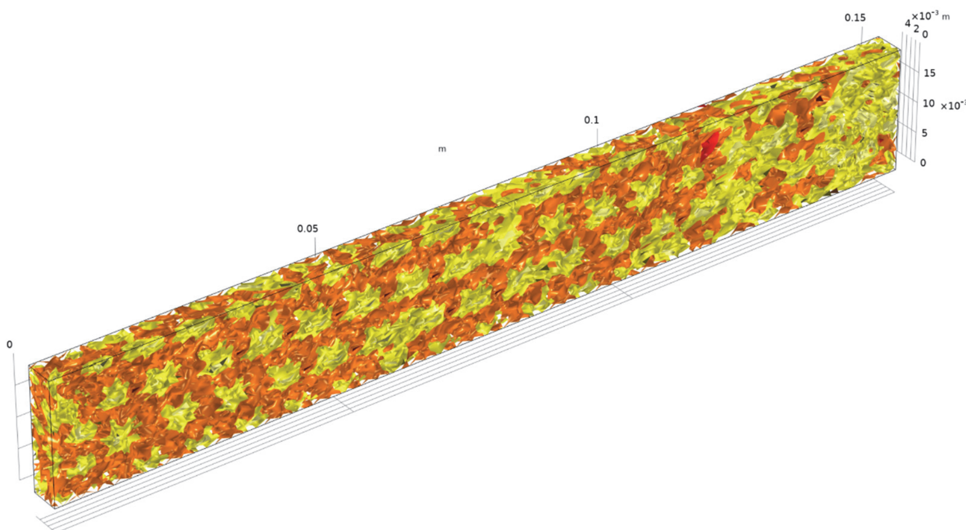

Figure 5: *COMSOL 3D model of the Gd plate with the change of the adiabatic temperature*

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).

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

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

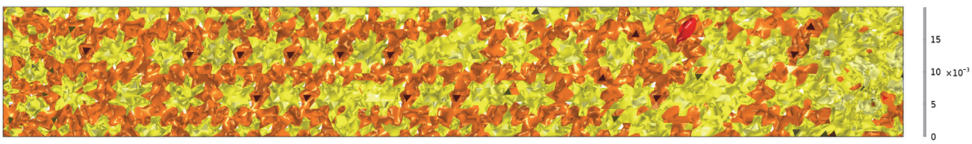

Figure 7: *COMSOL model of Gd board. with the change of the adiabatic temperature on the xz axis*

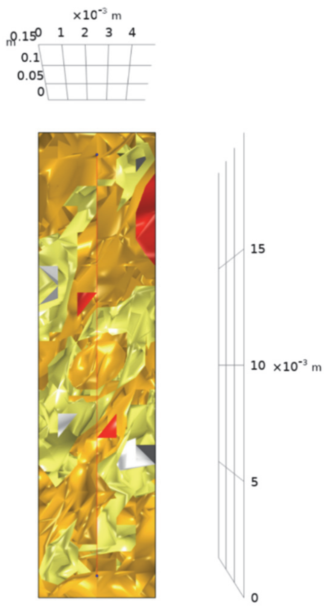

Figure 8: *COMSOL model of Gd. Board with the change of the adiabatic temperature on the yz axis.*

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].*

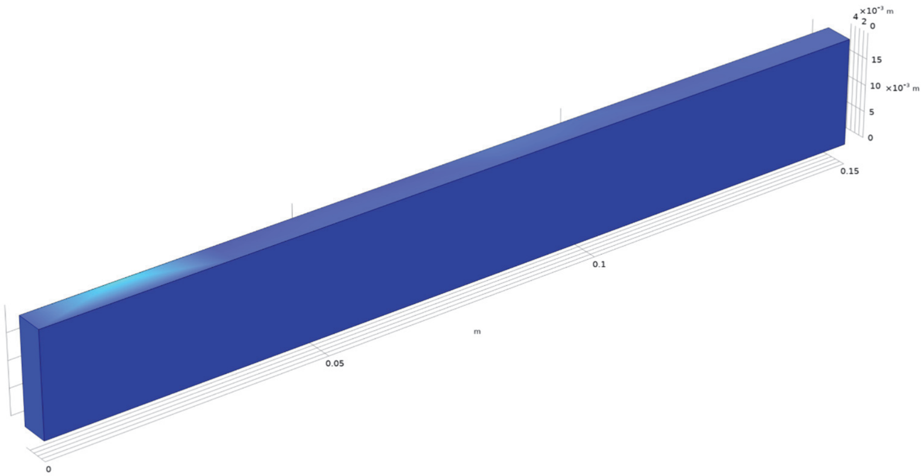

Figure 9: *3D model in COMSOL Multiphysics of the Gd plate inside the regenerator*

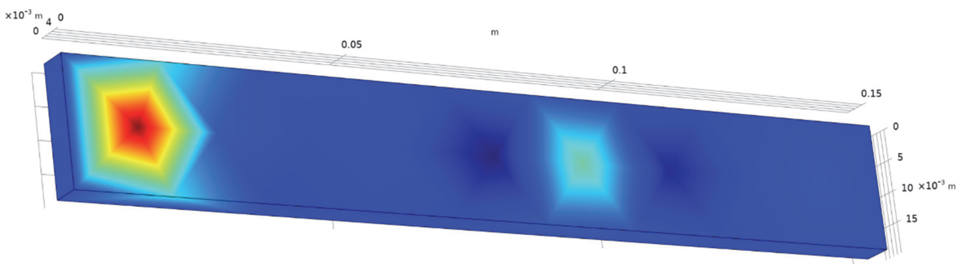

Figure 10: *3D model in COMSOL Multiphysics of Gd board used in AMR with temperature evolution*

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.

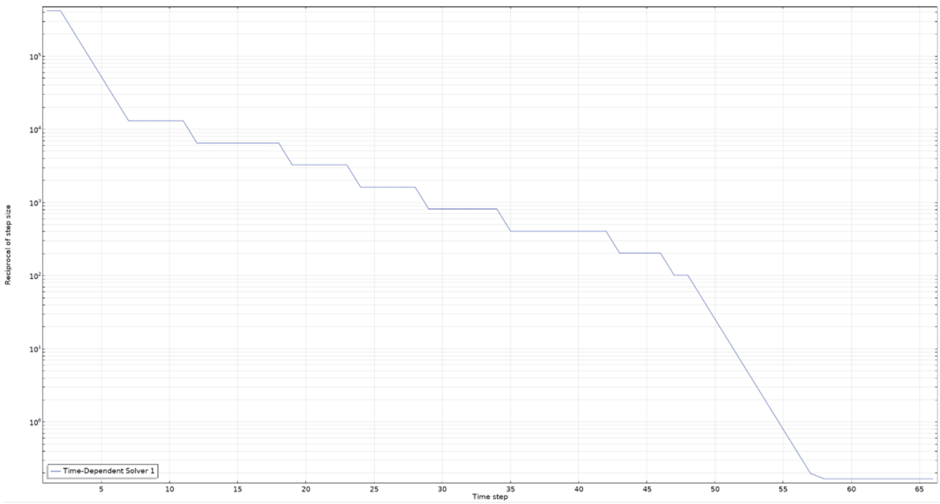

Figure 11: *Temperature variation in certain time intervals*

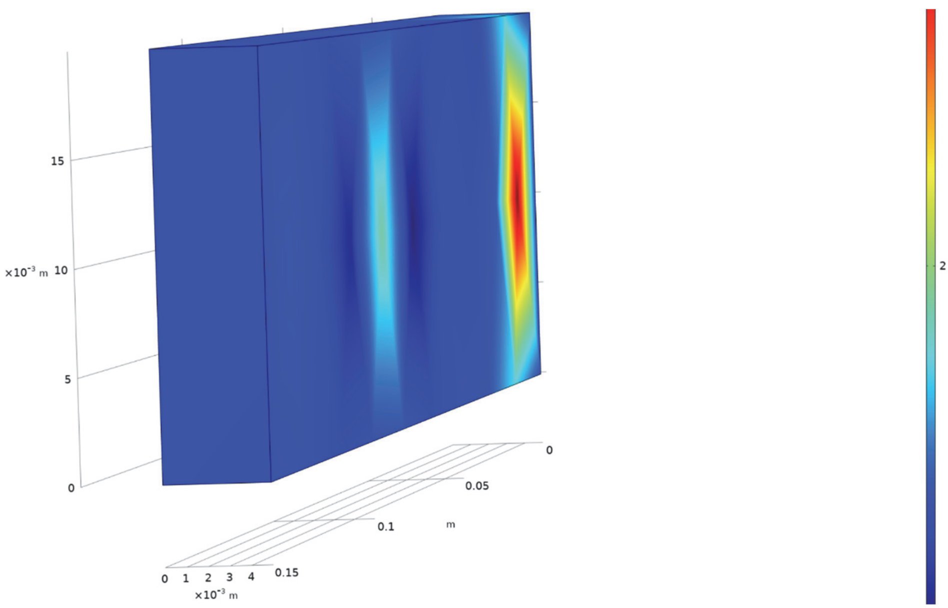

Figure 12: *COMSOL Multiphysics model of the Gd board. on the zy axis*

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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[2] **J. J. DiStefano, A.R. Stubberud, I. J. Williams**: *Theory and Problems of Feedback and Control Systems*, McGraw-Hill Book Company, 1987

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