International Institute of Refrigeration

COMMISSIONS B2, E2, A1

# THERMAG XI 2026

*IIR International Conference on Solid-State Cooling, Heating, and Energy Harvesting*

# BOOK OF ABSTRACTS


Editors: Katja Klinar, Andrej Kitanovski

University of Ljubljana, Faculty of Mechanical Engineering, Slovenia


| DATES | CITY | VENUE |
|---|---|---|
| 07 — 11 June, 2026 | Ljubljana, Slovenia | Cankarjev dom |

UNIVERSITY OF LJUBLJANA | FS Faculty of Mechanical Engineering

SZE Slovensko združenje za energetiko
Slovenian Energy Association

THE CHINESE ASSOCIATION OF REFRIGERATION 中国制冷学会

**THERMAG XI,** IIR International Conference on Solid-State Cooling, Heating, and Energy Harvesting
June 7-11, 2026, Ljubljana, Slovenia



**International Institute of Refrigeration**
**Institut International du Froid**
**IIR/IIF**
177 boulevard Malesherbes
75017 Paris
France
e-mail: iif-iir@iifiir.org

## IIR THERMAG CONFERENCE SERIES

The International Institute of Refrigeration (IIR) established the IIR Magnetic Cooling Working Party in 2004, with the inaugural conference held in Montreux, Switzerland, in 2005. The primary goal was to bring together materials scientists and engineers working in the field of magnetic cooling. Rapid advancements in other caloric technologies led to a growing number of participants at subsequent conferences. This growth eventually prompted a transition to include all caloric technologies under the umbrella of the so-called THERMAG conferences, which have since become a well-recognized and distinguished conference series dedicated to all caloric effects.

In 2022, the IIR decided to broaden its scope to encompass all solid-state technologies, aiming to enhance technology transfer across various disciplines, including cryogenics, refrigeration, heat pumping, energy harvesting, thermal management, thermal storage, and sensorics. Consequently, the new IIR Working Group on Solid-State Cooling and Heating was established. This group continues the THERMAG conference series, now enriched with a wider range of solid-state phenomena, to foster the development of practical applications and strengthen collaboration between research and industry.

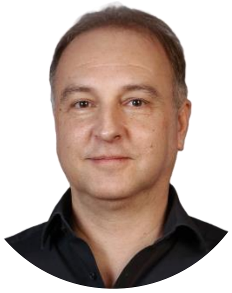
2005: 1st, Montreux, Switzerland
2007: 2nd, Portorož, Slovenia
2009: 3rd Iowa, USA
2010: 4th Baotou, China
2012: 5th, Grenoble, France
2014: 6th, Victoria, Canada
2016: 7th, Turin, Italy
2018: 8th, Darmstadt, Germany
2021: 9th, College Park, USA
2024: 10th, Baotou, China

**2026: 11th, Ljubljana, Slovenia**

## IIR THERMAG XI TOPICS

- Magnetocaloric or thermomagnetic materials and devices
- Mechanocaloric and thermomechanical material and devices
- Thermoelectric and magneto-thermoelectric materials and devices
- Thermal control devices: switches, diodes, regulators, transistors, thermal logic, circuits
- Solid-state laser cooling
- Electrocaloric or pyroelectric materials and devices
- Multicaloric and Multi-pyro materials and devices
- Spincaloritronic materials and devices
- Solid-state thermal storage materials and devices
- Other solid-state materials and related technologies

# FOREWORD



It is with great pleasure that we present the Book of Abstracts for the 11th IIR Conference on Solid-State Cooling, Heating and Energy Harvesting (Thermag XI), held in Ljubljana, Slovenia, from June 7–11, 2026.

This conference marks a significant milestone, as it unites several domains of solid-state cooling, heating, and energy harvesting technologies. By bringing together leading researchers, engineers, and industry experts from around the world, Thermag XI serves as a platform for sharing cutting-edge research on functional materials and their applications in energy systems.

The abstracts collected in this book reflect the breadth and depth of innovation presented at the conference. They span fundamental research, material development, device prototyping, modeling, and practical applications that are shaping the future of sustainable energy technologies.

We extend our sincere gratitude to all authors who submitted their work and to the reviewers whose expertise and dedication ensured the quality of this book. Special thanks go to the keynote speakers, session chairs, scientific committee, and organizers who made this event possible. We also acknowledge the support of the International Institute of Refrigeration (IIR), the Slovenian Energy Association (SZE), the Chinese Association of Refrigeration (CAR), the Faculty of Mechanical Engineering (FME) at the University of Ljubljana (UL), and all our sponsors and partners.

We hope this Book of Abstracts serves as a valuable resource for researchers and practitioners, inspiring new collaborations and advancing the transition toward efficient, environmentally friendly cooling, heating, and energy harvesting solutions.

Welcome to Thermag XI, and thank you for being part of this exciting scientific community.

Prof. Dr. Andrej Kitanovski

Conference Chair

Faculty of Mechanical Engineering, University of Ljubljana

Ljubljana, Slovenia

June 2026

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# PROGRAMME AT A GLANCE

## Sunday, Day 1

7 JUNE 2026

| TIME | ACTIVITY |
| --- | --- |
| 16:30 – 19:00 | Registration (Cankarjev dom) |
| 19:00 – 21:00 | **Social: Welcome reception (Cankarjev dom)** |

## Monday, Day 2

8 JUNE 2026

| TIME | ACTIVITY |
| --- | --- |
| 07:30 – 08:30 | Registration |
| 08:30 – 10:00 | **Opening ceremony with round table** |
| 10:00 – 10:30 | **Plenary: Prof. Björn Palm** |
| 10:30 – 11:00 | **Plenary: Prof. Ercang Luo** |
| 11:00 – 11:10 | **Social: Group photo** |
| 11:10 – 11:30 | **Break: Coffee break with posters & exhibition** |
| 11:30 – 13:30 | **Parallel: Session S01 · Session S02** |
| 13:30 – 14:30 | **Lunch: Lunch with posters and exhibition** |
| 14:30 – 16:30 | **Parallel: Session S03 · Session S04** |
| 16:30 – 17:30 | **Break: Coffee break with posters & exhibition** |
| 17:30 – 18:30 | **Parallel: Session S05 · Session S06** |
| 20:00 – 22:00 | **Social: Women in Science Event** |

**Women in Science Event**

**Venue: Ljubljana City Museum, Gosposka ulica 15, 1000 Ljubljana**

## Tuesday, Day 3

9 JUNE 2026

| TIME | ACTIVITY |
|---|---|
| 08:00 – 08:30 | Registration |
| 08:30 – 09:30 | **Sponsor's talks and projects** |
| 09:30 – 10:00 | **Plenary: Dr. Kilian Bartholomé** |
| 10:00 – 10:30 | **Plenary: Prof. Ken-ichi Uchida** |
| 10:30 – 11:00 | **Plenary: Prof. Jing-Feng Li** |
| 11:00 – 11:30 | **Break: Coffee break with posters & exhibition** |
| 11:30 – 13:30 | **Parallel: Session S07 · Session S08** |
| 13:30 – 14:30 | **Lunch Lunch with posters and exhibition** |
| 14:30 – 16:30 | **Parallel: Session S09 · Session S10** |
| 16:40 – 18:30 | **Social: Sightseeing tour of Ljubljana** |
| 20:00 – 23:00 | **Social: Conference dinner** |

**Sightseeing walking tour of Ljubljana**

**Meeting point: Registration desk**

**Conference dinner**

**Venue: Grand Hotel Union Eurostars (Grand Union Hall),**

**Miklosiceva cesta 1, 1000 Ljubljana**

## Wednesday, Day 4

10 JUNE 2026

| TIME | ACTIVITY |
|---|---|
| 08:00 — 09:00 | Registration |
| 09:00 — 09:30 | **Plenary: Prof. Baowen Li** |
| 09:30 — 10:00 | **Plenary: Prof. Suxin Qian** |
| 10:00 — 10:30 | **Plenary: Prof. Xavier Moya** |
| 10:30 — 11:00 | **Plenary: Prof. Zhang Jun** |
| 11:00 — 11:30 | **Break: Coffee break with posters & exhibition** |
| 11:30 — 13:30 | **Parallel: Session S11 · Session S12** |
| 13:30 — 14:30 | **Lunch: Lunch with posters and exhibition** |
| 14:30 — 16:30 | **Parallel: Session S13 · Session S14** |
| 16:30 — 18:00 | **Parallel:**<br>16:45 — 18:00 Session S15<br>16:45 — 17:45 Around-the-world electrocaloric characterization<br>16:30 — 17:45 IES Elastocalorics Workshop: Undergoing Rapid Transformation |
| 18:00 — 20:00 | **Special event: Cooling portfolio event** |
| 20:00 — 22:00 | **Social: Students event** |

**Special events:**

- **Around-the-world electrocaloric characterization**
  - organized by Prof. Emmanuel Defay in Linhart hall
- IES Elastocalorics Workshop: **Undergoing Rapid Transformation**
  - organized by IES in E2 room
- **Cooling portfolio event**
  - organized by the EIC in Linhart hall – free entrance

**Students event (Venue and information: TBA)**

## Thursday

11 JUNE 2026

| TIME | ACTIVITY |
|---|---|
| 08:00 – 09:00 | Registration |
| 09:00 – 09:30 | **Plenary: Prof. Victorino Franco** |
| 09:30 – 10:00 | **Plenary: Prof. Tsuyoshi Kawanami** |
| 10:00 – 10:30 | **Plenary: Prof. Pol Lloveras** |
| 10:30 – 11:00 | **Plenary: Prof. Xiaoshi Qian** |
| 11:00 – 11:30 | **Break: Coffee break** |
| 11:30 – 12:30 | **Parallel: Session S16 · Session S17** |
| 12:45 – 13:30 | **Social: Closing ceremony** |

# PLENARY TALKS

Special guests opening THERMAG XI on Monday morning.

PLENARY · SPECIAL GUEST

**Prof. Björn Palm**

KTH Royal Institute of Technology, Sweden

**Advancements in Vapour Compression: State of the art and perspectives**

10:00 MON · JUN 8 · LINHART HALL

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PLENARY · SPECIAL GUEST

**Prof. Ercang Luo**

Chinese Academy of Sciences, China

**Advancements in Thermoacoustics: State of the art and perspectives**

10:30 MON · JUN 8 · LINHART HALL

# TUESDAY PLENARIES

PLENARY

**Dr. Kilian Bartholomé**

Fraunhofer Institute IPM, Germany

**Advancements in Electrocaloric and Pyroelectric devices: State of the art and perspectives**

9:30 TUE · JUN 9 · LINHART HALL

PLENARY

**Prof. Ken-ichi Uchida**

National Institute for Materials Science, Japan

**Advancements in Spincaloritronic materials and devices: State of the art and perspectives**

10:00 TUE · JUN 9 · LINHART HALL

PLENARY

**Prof. Jing-Feng Li**

Tsinghua University, China

**Advancements in Thermoelectric materials and devices for heating, cooling, and energy harvesting: State of the art and perspectives**

10:30 TUE · JUN 9 · LINHART HALL

# WEDNESDAY PLENARIES

PLENARY

**Prof. Baowen Li**

Southern University of Science and Technology, China

**Advancements in Thermal control devices: State of the art and perspectives**

9:00 WED · JUN 10 · LINHART HALL

PLENARY

**Prof. Suxin Qian**

Xi'an Jiaotong University, China

**Advancements in Elastocaloric materials and devices: State of the art and perspectives**

9:30 WED · JUN 10 · LINHART HALL

PLENARY

**Prof. Xavier Moya**

University of Cambridge, UK

**Advancements in Barocaloric materials and devices: State of the art and perspectives**

10:00 WED · JUN 10 · LINHART HALL

PLENARY

**Prof. Zhang Jun**

Chinese Academy of Sciences, China

**Advancements in Solid State Laser Cooling: State of the art and perspectives**

10:30 WED · JUN 10 · LINHART HALL

# THURSDAY PLENARIES

PLENARY

**Prof. Victorino Franco**

University of Seville, Spain

**Advancements in Magnetocaloric and Thermomagnetic materials: State of the art and perspectives**

9:00 THU · JUN 11 · LINHART HALL

PLENARY

**Prof. Tsuyoshi Kawanami**

Meiji University, Japan

**Advancements in Magnetocaloric and Thermomagnetic devices: State of the art and perspectives**

9:30 THU · JUN 11 · LINHART HALL

PLENARY

**Prof. Pol Lloveras**

Polytechnic University of Catalonia, Spain

**Solid-State Thermal Storage: State of the art and perspectives**

10:00 THU · JUN 11 · LINHART HALL

PLENARY

**Prof. Xiaoshi Qian**

Shanghai Jiao Tong University, China

**High polar entropic design of electrocaloric materials**

10:30 THU · JUN 11 · LINHART HALL

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## S05 THERMOELECTRICS & MAGNETO-THERMOELECTRICS

## S06 MULTICALORICS & MULTIPYRO



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## MAGNETOCALORIC & THERMOMAGNETIC DEVICES

## MECHANOCALORIC & THERMOMECHANICAL DEVICES

## MECHANOCALORIC & THERMOMECHANICAL MATERIALS



## MULTICALORIC & MULTIPYRO MATERIALS



## THERMOELECTRIC & MAGNETO-THERMOELECTRIC MATERIALS

# THERMAG XI 2026

*IIR International Conference on Solid-State Cooling, Heating, and Energy Harvesting*

# PLENARIES

# CHALLENGES, ADVANCEMENTS AND PERSPECTIVES OF VAPOR COMPRESSION

**Bjorn Palm**

KTH Royal Institute of Technology, Sweden, Bjorn.Palm@energy.kth.se

## ABSTRACT

Heat pumping technologies, for heating and for cooling, will be extremely important in the near future. The need for cooling is expected to rise by a factor of 2 – 3 by 2050 due to increased temperatures and increased living standards. About half of the world´s energy use is for heating, and the main energy source is fossil fuels. To decarbonise the energy system by 2050 hundreds of millions of heat pumps need to be installed.

The dominating technology for heat pumping today is the vapor compression cycle. This technology has the advantages of being well developed, and of using a fluid (refrigerant) which changes in temperature during compression and expansion, which facilitates the heat transfer with the heat source and heat sink.

The synthetic fluids used as refrigerants have one or more negative effects on the environment: Contributing to ozone depletion, contributing to global warming, and contributing to spreading of PFAS such as TFA. However, the vapor compression cycle can also use natural refrigerants with no or low environmental impact, like carbon dioxide, ammonia and hydrocarbons. Due to the negative environmental effects of synthetic fluids, the industry is now moving towards the use of natural refrigerants.

In this presentation, different examples of such systems will be given, as well as examples of current research related to implementation of natural refrigerants.

**Keywords:** Refrigeration, Refrigerants, Vapor compression, Cooling, Heating, Heat pump

# ADVANCES OF THERMOACOUSTICS: THE STATE OF THE ART AND PERSPECTIVES

**Ercang Luo**

[(a)] The State Key Laboratory of Cryogenic Sciences and Technology, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, China, Beijing, 100190, China, ecluo@mail.ipc.ac.cn
[(b)] University of Chinese Academy of Sciences, China, Beijing, 100190, China

## ABSTRACT

Thermoacoustic technology is an emerging energy conversion and utilization technology characterized by its environmental friendliness, high reliability, and high efficiency, with significant development potential, and it holds great promise in various fields aimed at achieving carbon neutrality. This presentation will introduce the working principles of thermoacoustic heat engines, the latest progress in prototype development and theoretical research, as well as future application prospects. First, the progress in prototype research of thermoacoustic heat engines will be reviewed, including: (1) recent advances in thermoacoustic/Stirling power generation prototypes, particularly the development of free-piston thermoacoustic Stirling power generation technology; (2) progress in thermoacoustic heat-driven refrigeration prototypes, focusing on room-temperature and cryogenic refrigeration prototypes; and (3) advancements in thermoacoustic/Stirling heat pumps, especially those for extremely low-temperature ambient air-source heat pumps and high-temperature steam heat pump prototypes. Next, the theoretical research progress on thermoacoustic/Stirling heat engines will be presented, covering: (1) the thermodynamic cycle theory of thermoacoustic/Stirling heat engines, specifically the latest developments in LEC theory; (2) quantitative theoretical studies on thermoacoustic/Stirling heat engines, including progress in the theoretical modeling of time-averaged thermoacoustic effects; and (3) self-excited oscillation theory in thermoacoustic/Stirling heat engines, focusing on advances in time-domain nonlinear thermoacoustic network modeling. Finally, a brief overview of the development trends and application prospects of this technology will be outlooked.

**Keywords:** Advances, Thermoacoustics, Stirling, LEC cycle, Refrigeration, Power generation

**References:**

Hu, J. et al. (2025) 'A 100 kWe Free-piston Thermoacoustic-Stirling Electrical Generator', Proceedings of the 20th International Conference of Stirling Engine (ISEC), pp. 64–68.

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Luo, E. (2007) 'Non-Zero Time-Averaged Thermoacoustic Effects, Linear or Nonlinear?', International Cryocooler Conference (ICC), Cryocooler 14, pp. 195–203.

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Xiao, L., Luo, K., Wu, Z. et al. (2024) 'Sustainable heat-driven sound cooler with super-high efficiency', The Innovation Energy, 1(2), 100027

**Acknowledgement:** This work was financially supported by the State Key Research Project (No.2022YFF0712600), the State Key Laboratory of Cryogenic Science and Technology (CRYO20230103), and the National Natural Science Foundation of China (Grant No. 51976230).

# ADVANCEMENTS IN SPINCALORITRONIC MATERIALS AND DEVICES: STATE OF THE ART AND PERSPECTIVES

**Ken-ichi Uchida**[a,b]

[a] National Institute for Materials Science (NIMS)
Tsukuba, 305-0047, Japan, UCHIDA.Kenichi@nims.go.jp
[b] Department of Advanced Materials Science, Graduate School of Frontier Sciences, The University of Tokyo
Kashiwa, 277-8561, Japan, kuchida@edu.k.u-tokyo.ac.jp

## ABSTRACT

Spin caloritronics is a fusion research field that combines spintronics with thermoelectrics and thermal energy engineering (Uchida, 2021). In this field, many experimental and theoretical studies have focused on clarifying novel physics and functionalities arising from the interplay between heat, charge, and spin currents. One of the important functionalities realized by spin caloritronics is the transverse thermoelectric conversion, where heat and charge currents are interconverted in the orthogonal direction (Uchida, 2022; Adachi, 2025). This symmetry allows for a simpler structure of thermoelectric conversion modules compared to conventional Seebeck devices, thereby significantly enhancing their versatility. Materials science studies to enhance the transverse thermoelectric conversion performance is being conducted worldwide to realize next-generation energy harvesting and heat sensing technologies. In this talk, we will show history, recent progresses, and prospects of spin caloritronics and report on the status of research and development of the transverse thermoelectric conversion (Uchida, 2024; Hirai, 2024; Ando, 2025).

**Keywords:** Spin caloritronics, Transverse thermoelectrics, Thermal management, Magnetic material

**References:**

Adachi, H. et al. (2025) 'Fundamentals and advances in transverse thermoelectrics', Appl. Phys. Express 18(9), p. 090101. doi: 10.35848/1882-0786/adf700

Ando, F. et al. (2025) 'Multifunctional composite magnet realizing record-high transverse thermoelectric generation', Energy Environ. Sci. 18(9), pp. 4068-4079. doi: 10.1039/D4EE04845H

Uchida, K. (2021) 'Transport phenomena in spin caloritronics', Proc. Jpn. Acad., Ser. B 97(2), pp. 69-88. doi: 10.2183/pjab.97.004

Uchida, K. and Heremans, J. P. (2022) 'Thermoelectrics: from longitudinal to transverse', Joule 6(10), pp. 2240-2245. doi: 10.1016/j.joule.2022.08.016

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Hirai, T. et al. (2024) 'Hybridizing anomalous Nernst effect in artificially tilted multilayer based on magnetic topological material', Nat. Commun. 15, p. 9643. doi: 10.1038/s41467-024-53723-2

**Acknowledgement:** This work was supported by ERATO "Magnetic Thermal Management Materials" (grant no. JPMJER2201) from JST, Japan.

# ADVANCEMENTS IN THERMOELECTRIC MATERIALS AND DEVICES FOR HEATING, COOLING, AND ENERGY HARVESTING: STATE OF THE ART AND PERSPECTIVES

**Jing-Feng Li** [a,b]

[a]School of Materials Science and Engineering, Tsinghua University, Beijing, 100084 China,
jingfeng@mail.tsinghua.edu.cn

[b]Department of Applied Physics, Graduate School of Engineering, Tohoku University, Sendai, Japan

## ABSTRACT

Thermoelectric (TE) materials that can directly convert heat energy into electrical energy and vice versa are receiving increasing attention from both the scientific and industrial communities. The conversion efficiency of TE devices is highly dependent on the dimensionless figure of merit (ZT) of TE materials, defined as ZT = (α2σ/κ)T, where σ, κ and T are the electrical conductivity, thermal conductivity and absolute temperature, respectively. Achieving high ZT necessitates a delicate balance among three intrinsically coupled transport properties: high electrical conductivity, a large Seebeck coefficient, and low thermal conductivity- a challenge that has long impeded material optimization. Over the past two decades, however, substantial advances have been made in thermoelectric science and engineering. Continuous breakthroughs have been achieved in exploring high-performance thermoelectric materials not only in existing systems but also in new compounds. This presentation covers thermoelectric energy conversion principles, recent advances in high-performance thermoelectric materials, and key applications in energy harvesting, waste-heat recovery, and precision thermal management.

**Keywords:** Thermoelectric conversion technology, dimensionless figure of merit, materials development

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# ADVANCEMENTS IN THERMAL CONTROL DEVICES: STATE OF THE ART AND PERSPECTIVES

**Baowen Li**

Department of Physics, Shenzhen Key Lab for Phononics and Intelligent Thermal Materials, and State Key Lab of Quantum Functional Materials, Department of Materials Science and Engineering, Southern University of Science and Technology (SUSTech), Shenzhen, China

*Email：libw@sustech.edu.cn

## ABSTRACT

Thermal management is essential for many advanced technologies, including 3C electronics - computing, communication and consumer electronics - as well as humanoid robots, electric vehicles, eVTOL systems and data centres. In this talk, I will present recent developments in key thermal-management materials and devices, including thermal interface materials, thermal diodes, thermal switches, heat sinks and multifunctional thermal devices. I will also discuss recent applications of thermal diodes and thermal switches in solid-state cooling systems.

**Keywords:** thermal diode, thermal interfacial materials, solid state cooling

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# ADVANCEMENTS IN MAGNETOCALORIC AND THERMOMAGNETIC MATERIALS: STATE OF THE ART AND PERSPECTIVESR

**Victorino Franco, Zhe Cui, Carlos Romero-Muñiz, Jorge Revuelta-Losada, Alejandro Descalzo-Ruiz, Zhonghao Chang, Elisa Guisado-Arenas, José M. Gordón-Pidal, Jia Yan Law**

Multidisciplinary Unit for Energy Science, University of Seville, Spain, vfranco@us.es

## ABSTRACT

Evaluating the state-of-the-art in solid-state thermal management requires navigating evolving trends across material families, balancing primary magnetocaloric performance with critical secondary properties. Attention increasingly focuses on sustainable, compositionally complex alloys (Klinar et al., 2024). However, navigating their vast compositional space while designing for performance presents a severe combinatorial bottleneck as conventional first-principles accuracy is computationally too expensive. To overcome this, we introduce a physics-informed machine learning framework based on a minimal-supercell principle (Cui et al., 2026). By demonstrating that magnetostructural behavior emerges from local atomic environments, this framework efficiently maps global design spaces to optimize thermomagnetic phase transformations. Beyond compositional exploration, characterization of the materials should be performed in experimental conditions that mimic their actual operation inside the device, paying attention to reversibility and hysteresis, especially for complex-shaped regenerators.

**Keywords:** Magnetocaloric materials; vast compositional space computational search; computational design; hysteresis; reversibility; characterization

**References:**

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# ADVANCEMENTS IN MAGNETOCALORIC AND THERMOMAGNETIC DEVICES: STATE OF THE ART AND PERSPECTIVES

**Tsuyoshi Kawanami**

Department of Mechanical Engineering Informatics, Meiji University
Kawasaki, 214-8571, Japan, kawanami@meiji.ac.jp

## ABSTRACT

Magnetic thermal technologies have advanced significantly over the past decades through the development of high-performance magnetocaloric materials and innovative system architectures. This plenary lecture reviews recent progress in magnetocaloric and thermomagnetic devices from the perspective of thermal management and temperature-gradient control. After briefly tracing the evolution of magnetic refrigeration, key challenges in active magnetic regenerators (AMRs) are discussed, with particular emphasis on the gap between material-level and system-level performance. Strategies for preserving thermal gradients and improving thermal stability are presented, together with recent developments in thermomagnetic devices for thermal-energy conversion and waste-heat utilization. Finally, future perspectives on integrated magnetic thermal-energy systems are discussed, highlighting the growing role of thermal management as a unifying framework for next-generation cooling, heat-pumping, and energy-conversion technologies.

**Keywords:** Active Magnetic Regenerator (AMR), Magnetocaloric Refrigeration, Thermomagnetic Energy Conversion, Thermal Management

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# SOLID-STATE THERMAL STORAGE: STATE OF THE ART AND PERSPECTIVES

**Pol Lloveras**

Group of Characterization of Materials, Department of Physics and Barcelona Research Center in Multiscale Science and Engineering, Universitat Politècnica de Catalunya, Barcelona, 08019, Spain

pol.lloveras@upc.edu

## ABSTRACT

Thermal Energy Storage (TES) is becoming increasingly important as a key technology for enhancing energy efficiency and environmental sustainability across a wide range of applications. TES impacts areas as diverse as solar energy, industrial waste heat, renewable electricity and thermal management of cold-chain logistics, electronics and wearables. The variety of uses, scales, operation frequencies and temperature ranges critically influence system and material requirements. While established technologies hinder market adoption, substantial opportunities remain for advances in materials science and engineering to develop innovative solid-state thermal storage solutions that can compete with existing approaches and enable novel applications. Here, an overview of TES applications, systems and materials will be provided.

**Keywords**: Thermal Energy Storage, latent heat, solid-state phase change materials, organics, hybrids, metallic alloys.

# HIGH POLAR ENTROPIC DESIGN OF ELECTROCALORIC MATERIALS

**Xiaoshi Qian[(a)], Donglin Han[(a)], Shangyu Zheng[(a)], Feihong Du[(a)]**

[(a)] Shanghai Jiao Tong University, Shanghai, 200240, China, xsqian@sjtu.edu.cn

## ABSTRACT

Materials exhibiting a high electrocaloric effect (ECE) tend to favor a disordered yet easily tunable polar structure. This talk will show that by processing the polar structure into a high polar entropy state, the ECE in both polymeric and ceramic materials can be markedly improved. We synthesized the P(VDF-TrFE-CFE-DB) tetrapolymer and the interface-augmented P(VDF-TrFE-CFE) that exhibited increased crystallinity, and reduced crystalline size. The resulting EC polymer presented a near 300% enhancement of ECE at the low fields. The strategy seems working for inorganics as well, we developed a lead-free relaxor ferroelectric with strong polar disorder via targeted multielement substitution at both the A- and B-sites of the perovskite oxide. These multielement-induced features led to an increased density of interfaces, significantly enhancing the polar entropy. A high ECE of an isothermal entropy change ΔSiso ~ 15 J kg-1K-1 under a 10 MV m-1 field is observed. The formation of ultrafine dispersed, multiphase dipole configurations leads to high-polar entropy electrocalorics that sustain a long lifetime of large ECE over 3 million cycles.

**Keywords:** High polar entropy, electrocaloric materials, dipole correlation, on-chip cooling.

**Acknowledgement:** NSFC

# THERMAG XI 2026

*IIR International Conference on Solid-State Cooling, Heating, and Energy Harvesting*

# ORAL PRESENTATIONS

*ORAL PRESENTATIONS*

## S01 Mechanocalorics & Thermomechanics LINHART HALL

Chair **Pol Lloveras** · Co-chair **Žiga Ahčin** · Help **Tomaž Pšeničnik**

11:30 Giant tunable barocaloric effects using guest-molecule adsorption in a metal-organic framework
**Melony Dilshad** · *University of Cambridge*

11:42 Barocaloric effect in hybrid organic-inorganic perovskite-like compounds
**Emmanouil Charkiolakis** · *INMA, CSIC, UniZar*

11:54 Investigation of barocaloric and phase transition supercooling in plastic crystals
**Yi Tang** · *University of Cambridge*

12:06 Room-temperature barocaloric effect in a spin-crossover material
**Vera Cuartero** · *INMA — University of Zaragoza*

12:18 Barocaloric effect in neopentylglycol (NPG) / natural rubber composite
**Baris Emre** · *Ankara University*

12:30 Thermoelastic harvesting of low-grade waste heat
**Sebastian Fähler** · *Helmholtz-Zentrum Dresden-Rossendorf*

12:42 Heat-to-power energy conversion using thermomechanical polymers: an experimental proof of concept
**Gaël Sebald** · *INSA Lyon — CNRS — Tohoku University*

12:54 Elastocaloric cooling with thin films achieving ultra-high fatigue lifetimes
**Navid Sistanizadeh-Aghdam** · *IMT, Karlsruhe Institute of Technology*

13:06 Film-based heat-driven elastocaloric cooling
**Yi-Ting Hsiau** · *Karlsruhe Institute of Technology*

13:18 Performance of SMA actuators driven by low-grade heat source
**Wang Xiangyu** · *Xi'an Jiaotong University*

# GIANT TUNABLE BAROCALORIC EFFECTS USING GUEST-MOLECULE ADSORPTION IN A METAL-ORGANIC FRAMEWORK

**Melony Dilshad**[(a)], **Giulio Lampronti**[(a)], **Thomas D. Bennett**[(b)], **Xavier Moya**[(a)]

[(a)] Department of Materials Science & Metallurgy, University of Cambridge, Cambridge CB3 0FS, UK

[(b)] MacDiarmid Institute for Advanced Materials and Nanotechnology, School of Physical and Chemical Sciences, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand

md712@cam.ac.uk, xm212@cam.ac.uk

## ABSTRACT

Metal-organic frameworks (MOFs) that exhibit first-order structural phase transitions with significant volume changes are promising candidates for barocaloric cooling and heating applications (Boldrin, 2021). Here we report giant barocaloric effects in a zeolitic-imidazolate framework [ZIF-4(Zn)] that can be reversibly driven over a wide range of temperatures with pressure, near a starting temperature that is highly tunable using gas adsorption. For nitrogenated frameworks of ZIF-4(Zn), we report isothermal entropy changes over $|\Delta S_{it}| > 38$ J K$^{-1}$ kg$^{-1}$ and adiabatic temperature changes over $|\Delta T_{ad}| > 10$ K driven by $|\Delta p| = 1$ kbar near $T_0 \sim 190$ K. For desolvated frameworks of ZIF-4(Zn), we report larger barocaloric effects of $|\Delta S_{it}| \sim 210$ J K$^{-1}$ kg$^{-1}$ and $|\Delta T_{ad}| \sim 60$ K near $T_0 \sim 137$ K driven using the same pressure change. Our findings should establish a benchmark for MOFs as environmentally benign solid-state refrigerants that can be tuned using guest molecules.

**Keywords:** Metal-organic frameworks, gas adsorption, barocaloric

**References:** Boldrin, D. (2021). Fantastic barocalorics and where to find them. Applied Physics Letters, 118(17), p.170502. doi: https://doi.org/10.1063/5.0046416.

**Acknowledgement:** This work was supported by the EPSRC grant EP/V042262/1. X. M. is grateful for support from the Royal Society.

# BAROCALORIC EFFECT IN HYBRID ORGANIC-INORGANIC PEROVSKITE-LIKE COMPOUNDS

**Emmanouil K. Charkiolakis[(a)], David Gracia[(a)], Vera Cuartero[(a)], Javier Blasco[(a)], Gloria Subías[(a)], Marco Evangelisti[(a)]**

[(a)] Instituto de Nanociencia y Materiales de Aragón (INMA), CSIC & Universidad de Zaragoza, Zaragoza,50009, Spain, e-mail charkiolakis@unizar.es

## ABSTRACT

The development of efficient solid-state cooling technologies relies heavily on the discovery of materials exhibiting strong caloric responses to external stimuli. Among them, barocaloric materials provide a promising route toward environmentally friendly refrigeration. Here, we report a detailed investigation of the barocaloric behavior of hybrid organic-inorganic perovskite-like compounds (C9-M) (Li et al., 2021), (Kammoun et al., 1998). A combination of adiabatic calorimetry, high-pressure calorimetry, powder X-ray diffraction (PXRD), and synchrotron-based PXRD experiments was employed to elucidate the structural and thermodynamic responses to hydrostatic pressure. The results reveal that only part of the material undergoes a reversible phase transition, resulting in the coexistence of three distinct phases. This pressure-induced phase mixture is directly correlated with an impressive barocaloric effect near room temperature, underscoring the interplay between structural flexibility, phase heterogeneity, and thermodynamic properties.

**Keywords:** Barocaloric Effect, Hybrid organic-inorganic materials, High-pressure calorimetry, Synchrotron X-ray diffraction

**References:**

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**Acknowledgement:** This work has received support from ERDF/EU (PID2021-124734OB-C21, CEX2023-001286-S), Gobierno de Aragón (E11-23R, E12-23R).

# INVESTIGATION OF BAROCALORIC AND PHASE TRANSITION SUPERCOOLING IN PLASTIC CRYSTALS

**Yi Tang[(a)], Xavier Moya[(a)]**

[(a)] University of Cambridge, Department of Material Science and Metallurgy, Cambridge, CB3 0FS,
yt399@cam.ac.uk

## ABSTRACT

Compared to vapor-compression cycles using high-GWP gases, barocaloric cooling offers quiet operation, high power density, and reduced climate impact. However, translating this promise into practical devices requires overcoming several challenges: achieving significant, reversible temperature/entropy changes at reasonable pressures, reducing hysteresis and performance drift during cycling, and ensuring efficient heat exchange in actual components.

In this work, we investigate how morphology affects supercooling and barocaloric performance. Using high-pressure calorimetry data and in-situ x-day diffraction explained how the morphological factors and structural transition could optimize the microstructure enhances the phase transition features in plastic crystals. Based on these findings, we provide straightforward processing and integration guidelines for stable, application-ready operation.

**Keywords:** Barocaloric, Energy storage, Supercooling, Phase transition

# ROOM-TEMPERATURE BAROCALORIC EFFECT IN A SPIN-CROSSOVER MATERIAL

**David Gracia,[(a)] Vera Cuartero,[(a)*] Catalin Popescu,[(b)] Adelais Trapali,[(c)] Talal Mallah,[(c)] Marie-Laure Boillot,[(c)] Javier Blasco,[(a)] Gloria Subías,[(a)] Marco Evangelisti[(a)]**

[(a)] Instituto de Nanociencia y Materiales de Aragón (INMA), CSIC-Universidad de Zaragoza, 50009 Zaragoza, Spain

[(b)] CELLS - ALBA Synchrotron, 08290 Cerdanyola del Valles, Barcelona, Spain

[(c)] Institut de Chimie Moléculaire et des Matériaux d'Orsay, CNRS UMR 8182, Université Paris-Saclay, 91400 Orsay, France

* vcuartero@unizar.es

## ABSTRACT

The goal of this work is to evaluate the barocaloric potential of [Fe(pap-5$NO_2$)$_2$] compound by examining the pressure dependence of the spin-crossover transition, occurring near room temperature (Iasco et al., 2015). We employ a combination of high-pressure calorimetry and powder x-ray diffraction measurements, conducted both under variable-pressure and variable-temperature conditions. Both methods indicate that the spin-crossover transition shifts linearly to higher temperatures with increasing pressure, while simultaneously exhibiting an increase in the width of the thermal hysteresis. We report a giant barocaloric effect, revealing isothermal entropy changes in the $70 - 79$ J $kg^{-1}$ $K^{-1}$ range and adiabatic temperature changes between 20 and 26 K for a pressure change of 2 kbar (Gracia et al., 2025). Although the effect diminishes under reversible conditions, it remains significantly large when compared to other spin-crossover compounds. When compared with other barocalorics, [Fe(pap-5$NO_2$)$_2$] compound stands out due to its operational temperatures being closer to room temperature, underscoring its potential in practical applications.

**Keywords:** barocaloric effect, spin-crossover compounds, x-ray diffraction under pressure, high-pressure calorimetry

**References:**

Gracia, D., Cuartero, V., Popescu, C., Trapali, A., Mallah, T., Boillot, M.-L., Blasco, J., Subías, G. and Evangelisti, M. (2025) 'Room-temperature barocaloric effect in [Fe(pap-5NO2)2] spin-crossover material', *Journal of Materials Chemistry A*, 13(23), pp. 17944–17951. doi: 10.1039/D5TA00033E

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**Acknowledgement:** This work was funded by MICIU/AEI/10.13039/501100011033 and ERDF/UE (PID2021-124734OB-C21, CEX2023-001286-S), Gobierno de Aragón (E11-23R, E12-23R) and Fundación Ibercaja and Universidad de Zaragoza (JIUZ2023-CIE-05). D.G. acknowledges financial support from the Gobierno de Aragón through a doctoral fellowship. The authors acknowledge the Servicio General de Apoyo a la Investigación from Universidad de Zaragoza, ALBA synchrotron for granting beamtime (experiment no. 2023027379), and MSPD beamline staff for experimental and technical support.

# BAROCALORIC EFFECT IN NEOPENTYLGLYCOL (NPG)/NATURAL RUBBER COMPOSITE

**Baris Emre[a,b], Süheyla Yüce[c,b], Eyüp Kavak[a], Melony Dilshad[b], Lluís Mañosa[d], Xavier Moya[b]**

[a]Department of Engineering Physics, Faculty of Engineering, Ankara University, Ankara, 06100, Türkiye, bemre@eng.ankara.edu.tr

[b]Department of Materials Science, University of Cambridge, Cambridge CB3 0FS, UK,

[c]Department of Physics, Faculty of Science, Ondokuz Mayis University, Samsun, 55139, Türkiye,

[d] Departament de Fisica de la Matèria Condensada, Facultat de Fisica, Universitat de Barcelona, Barcelona, 08028, Catalonia.

## ABSTRACT

Plastic crystals, a class of materials characterized by orientationally disordered yet translationally ordered molecular structures, have attracted significant attention as high-performance barocaloric materials for solid-state cooling applications. Their unique combination of soft lattice dynamics and strong coupling between pressure and molecular orientation results in exceptionally large entropy changes under moderate hydrostatic pressures. This pressure-driven order–disorder transition gives rise to colossal barocaloric effects, often comparable to or exceeding those observed in magnetocaloric and electrocaloric materials (Lloveras et al., 2019). NPG, a prototypical plastic crystal, has emerged as one of the most promising materials for achieving colossal barocaloric effects in solid-state cooling applications. This transition is accompanied by large entropy and volume changes, which can be reversibly tuned by applying moderate hydrostatic pressures (Lloveras et al., 2019). Recently, potential of polymer composite films as caloric materials for environmentally friendly solid-state refrigeration was reported (Lünser et al., 2024). In this work, we report the NPG/natural rubber composite as efficient, sustainable, and tunable barocaloric materials for next-generation solid-state cooling systems.

**Keywords:** Barocaloric, plastic crystal, natural rubber, composite

**References:**

Lloveras, P., Aznar, A., Barrio, M., Negrier, P., Popescu, C., Planes, A., Mañosa, L., Stern-Taulats, E., Avramenko, A., Mathur, N.D. and Moya, X. (2019) 'Colossal barocaloric effects near room temperature in plastic crystals of neopentylglycol', *Nature Communications*, 10(1), p. 1803. doi: 10.1038/s41467-019-09730-9.

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# THERMOELASTIC HARVESTING OF LOW-GRADE WASTE HEAT

**Bruno Neumann[a,b], Morik Nikolic[a,c], Andreas Henschke[a], Razie Mohamadi[a,b], Sebastian Fähler[a]**

[a] Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany

[b] Faculty of Mechanical Science and Engineering, TUD Dresden University of Technology, 01062 Dresden, Germany

[c] Hochschule für Technik und Wirtschaft Dresden – University of Applied Sciences, Faculty of Mechanical Engineering, Friedrich-List-Platz 1, 01069 Dresden, Germany

s.faehler@hzdr.de

## ABSTRACT

Ferroic properties enables caloric cooling, which is the core scope of this conference. In addition, these functional materials allow for harvesting low-grade waste heat, and recent breakthroughs in thermomagnetic and pyroelectric devices make this complementary energy conversion process the second key scope of this conference. However, among ferroic materials, ferroelastic materials like shape memory alloys had been mostly used only for elastocaloric refrigeration, but rarely for energy harvesting.

Here we present experiments and simulations of a novel thermoelastic harvester design. It uses commercial NiTi shape memory wires in a protagonist-antagonist setup, which re-covers the mechanical energy required for prestraining. For our device we analyze the influence of key design and operational parameters, which include temperatures, prestrain, and workload. At optimized conditions, our thermoelastic generator outperforms other ferroic harvesting devices with respect to power density, total output power, and thermodynamic efficiency.

**Keywords:** ferroic energy harvesting, low-grade waste heat recovery, thermoelastic generator

**Acknowledgement:** This project is funded by DFG, project FA452/17-1.

# HEAT TO POWER ENERGY CONVERSION USING THERMOMECHANICAL POLYMERS: AN EXPERIMENTAL PROOF OF CONCEPT

**Gael Sebald[(a)], Giulia Lombardi[(a)], Oiri Takuma[(b)], Gildas Coativy[(c)], Atsuki Komiya[(a,b)]**

[(a)] ELyTMaX IRL 3757, CNRS, Univ. Lyon, INSA Lyon, Centrale Lyon, Université Claude Bernard Lyon 1, Sendai, 980-8577, Japan.

[(b)] Institute of Fluid Science, Tohoku University, 2-1-1, Katahira, Aoba-ku, Sendai, 980-8577, Japan.

[(c)] INSA Lyon, LGEF, UR682, 8 Rue de la Physique, Villeurbanne, 69621, France.

Correspondence: Gael Sebald, gael.sebald@insa-lyon.fr, ELyTMaX IRL3757, Tohoku University, Aoba- Ku, Katahira 2-1-1, MaSC#503, 980-8577 Sendai, Japan. +81 22 217 6609

## ABSTRACT

Low-grade heat although abundant is hardly convertible into usable energy not only because of the limited Carnot efficiency, but also due to the lack of proper solutions, especially at low scales. In this work, we investigated the thermomechanical properties of natural rubber and proposed a design of a heat to power energy converter. The thermomechanical characterization of natural rubber tubes showed temperature induced stress variation up to 9~12 kPa/K for elongations between 3 and 6 times the initial length. A device was then developed using a dual assembly of parallel natural rubber tubes. Temperature variations of 5 ~ 35 K were then induced by cyclic flow between hot and cold reservoirs. Applying thermodynamic cycles, the prototype was able to produce up to 3.2 J of mechanical energy per cycle (150 mJ/cm$^3$ per cycle). Considering the cycle period of 34 s, this corresponded to an output mechanical power of 120 mW.

**Keywords**: heat to power, thermomechanical, natural rubber, low grade heat conversion

**References:** Sebald, G., Lombardi, G., Coativy, G., Komiya, A., (2025) “Converting low-grade heat into mechanical energy using a natural rubber elastocaloric device”, *Joule*, **9(7)**, 102012. (doi: 10.1016/j.joule.2025.102012)

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# ELASTOCALORIC COOLING WITH THIN FILMS ACHIEVING ULTRA-HIGH FATIGUE LIFETIMES

**Navid S. Aghdam[(a)], Lars Bumke[(b,c)], Eckhard Quandt[(b)], Manfred Kohl[(a)], Jingyuan Xu[(a)]**

[(a)] Institute of Microstructure Technology, Karlsruhe Institute of Technology, Hermann-von-Helmholtz Platz 1, Eggenstein-Leopoldshafen, 76344, Germany, navid.aghdam@kit.edu, +49 721 608-23940

[(b)] Faculty of Engineering, Kiel University, Kiel, 24143, Germany

[(c)] Acquandas GmbH, Kiel, 24143, Germany

## ABSTRACT

Efficient thermal management at the microscale is essential for next-generation electronics and photonics, yet current cooling technologies remain limited in scalability, efficiency, and sustainability. Elastocaloric cooling using micrometer-thick shape memory alloy (SMA) films offers a promising route through high surface-to-volume ratios and fast heat transfer. However, the practical use of SMA thin films has been restricted by poor fatigue lifetimes under tensile loading. Here, we demonstrate elastocaloric thin-film devices achieving over 10 million fully reversible tensile cycles, representing a four-order-of-magnitude improvement over previous devices. This breakthrough is enabled by ultra-low-fatigue TiNiCuCo SMA films and a mechanically optimized device architecture featuring adjustable clamping and stress-optimized geometries. The device exhibits stable performance with no degradation and specific cooling power up to 12.6 W $g^{-1}$. These results establish a pathway toward durable, high-performance elastocaloric cooling for fast and efficient microscale thermal management.

**Keywords:** Elastocaloric cooling, Fatigue resistance, Microscale cooling, Shape memory alloys, Thin-film devices

**Acknowledgement:** This work was funded by the Carl-Zeiss-Stiftung through the CZS Nexus project, the Baden-Württemberg Stiftung through the Eliteprogramme for Postdoctoral Researchers, and the Hector Fellow Academy. This work was partly carried out with the support of the Karlsruhe Nano Micro Facility (KNMF, www.knmf.kit.edu), a Helmholtz Research Infrastructure at Karlsruhe Institute of Technology (KIT, www.kit.edu). LB and EQ acknowledge funding by the German Science Foundation (DFG) through project 413288478. We thank Huayu Liu for valuable assistance with the FEM simulations and Gowtham Arivanandhan for acquiring the SEM images.

# FILM-BASED HEAT-DRIVEN ELASTOCALORIC COOLING

**Yi-Ting Hsiau[(a)], Shuichi Miyazaki[(b)], Manfred Kohl[(a)], Jingyuan Xu[(a)]**

[(a)] Institute of Microstructure Technology, Karlsruhe Institute of Technology Karlsruhe, 76021, Germany, jingyuan.xu@kit.edu

[(b)]Division of Material Science, University of Tsukuba Tsukuba, 305-8573, Japan

## ABSTRACT

Elastocaloric cooling is recognized as a promising solid-state cooling technology. Conventional elastocaloric systems typically use electrically driven actuators to load the elastocaloric material. In this work, we present a novel heat-actuated elastocaloric cooling device driven by a film-based shape memory alloy (SMA) actuator, designed to utilize low-grade thermal energy. The developed thermally responsive actuator achieves a driving stroke of 380 µm with sufficient force to induce a martensitic transformation in the elastocaloric refrigerant film. At a required heating temperature of 86 °C, the refrigerant film in our device achieves a temperature span of 12.9 K under thermal actuation. This work demonstrates the feasibility of integrating thermal actuation with film-based SMA elastocaloric cooling, paving the way for thermally driven solid-state cooling systems.

**Keywords:** Elastocaloric cooling, Shape memory alloy (SMA), SMA thermal actuator, Heat-driven cooling

**Acknowledgement:** This project is funded by the Carl-Zeiss-Stiftung, Baden-Württemberg Stiftung and the Hector Fellow Academy.

# PERFORMANCE OF SMA ACTUATORS DRIVEN BY LOW-GRADE HEAT SOURCE

**Xiangyu Wang[(a)], Yao Wang[(a)], Ye Liu[(a)], Jianlin Yu[(a)], Suxin Qian[(a)]**

[(a)] Department of Refrigeration and Cryogenic Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, People's Republic of China, 4124103222@stu.xjtu.edu.cn

## ABSTRACT

Elastocaloric cooling has attracted attention for its zero global warming potential and high theoretical energy efficiency, but the bulky actuators required hinder practical application. Accordingly, high-energy-density heat-driven shape-memory alloy (SMA) actuators are being considered. To evaluate the performance of heat-driven SMA actuators, this study developed a multimodal SMA thermomechanical test platform. It incorporates three testing modes, including constant force, constant displacement, and linear force variation. A servo motor was used to precisely simulate the driving characteristics of heat-driven SMAs under diverse mechanical loads. Experimental results demonstrate that under cyclic thermal variations from 20 to 90°C, heat-driven SMAs achieve a maximum reversible stress of 662 MPa, a maximum reversible strain of 2%, a specific gravimetric output force of 693.3 $N \cdot g^{-1}$, and an energy density of up to 6.26 $J \cdot cm^{-3}$. This study provides crucial experimental evidence and design guidance for the subsequent development of low-electricity-consumption, small-sized elastocaloric cooling systems.

**Keywords:** Elastocaloric cooling, Heat-activated cooling, Shape-memory alloy.

*ORAL PRESENTATIONS*

## S02 Magnetocalorics & Thermomagnetics KOSOVEL HALL

Chair **Jierong Liang** · Co-chair **Guilherme Fidelis Peixer** · Help **Kamyar Dobakhti**

**11:30** Magnetic cooling — from lab to market
**Dimitri Benke** · *Magnotherm Solutions GmbH*

**11:42** Design and challenges of a large-scale magnetic cooling unit for industrial refrigeration
**Sergiu Lionte** · *Magnoric*

**11:54** High-efficiency regenerators based on $La(Fe,Mn,Si)_{13}$-H
**Edmund Lovell** · *Camfridge Ltd*

**12:06** Design and optimisation of a compact magnetic cooling unit for commercial refrigeration
**Hugo Du Moulinet d'Hardemare** · *Magnoric*

**12:18** How one prototype is shaping next-generation magnetic refrigerators
**Stefano Dall'Olio** · *EFC Mag*

**12:30** Terbium — a magnetocaloric material of the extreme
**Tino Gottschall** · *Helmholtz-Zentrum Dresden-Rossendorf*

**12:42** Multifunctional high-entropy alloys for caloric applications
**Vincent Fournée** · *Institut Jean Lamour, CNRS — Univ. de Lorraine*

**12:54** Disentangling conventional, anisotropic, structural and electronic contributions to the magnetocaloric effect in multifunctional magnetic materials
**Konstantin Skokov** · *TU Darmstadt*

**13:06** Phase transitions and caloric effects in $Hf_{0.84}Ta_{0.16}Fe_2$
**Luana Caron** · *Bielefeld University*

**13:18** Modeling the magnetocaloric behaviour of $Ho_{1-x}Er_xAl_2$ within a mean-field framework
**Bruno Alho** · *Rio de Janeiro State University*

# MAGNETIC COOLING – FROM LAB TO MARKET

**Dimitri Benke, Jeffrey Pickett, Tim Sittig, Christopher Fujta, Jonas Stötzer, Martin Lehmann, Milan Strauch, Max Greifenstein, Max Fries**

Magnotherm Solutions GmbH

Darmstadt, 64297, Germany, benke@magnotherm.com

## ABSTRACT

Magnetic cooling has been investigated for more than 25 years, with numerous prototype systems demonstrating the fundamental feasibility of the technology. However, only a limited number of systems have progressed to application-level integration while delivering the cooling power and efficiency required to compete with conventional vapor-compression technology.

As a first application-oriented device, we developed POLARIS, a magnetic beverage cooler. While this system successfully validated integration into an end-use product, it did not reach the cooling power necessary to match the performance of conventional beverage coolers. Building on these insights, we developed ECLIPSE, a versatile magnetic cooling platform designed for integration into horizontal and vertical supermarket refrigeration cabinets as well as water-chiller applications. ECLIPSE achieves more than 600 W of cooling power at a 20 K temperature span and exceeds 1000 W at lower spans.

In this contribution, we present the progression of our prototypes toward higher system-level performance. We highlight the distinction between the thermodynamic efficiency of the magnetic cooling cycle itself and the realized efficiency of the integrated system, thereby outlining key challenges and opportunities for advancing magnetic cooling toward commercial competitiveness.

**Keywords:** Magnetic cooling device, commercialization, AMR

# DESIGN AND CHALLENGES OF A LARGE-SCALE MAGNETIC COOLING UNIT FOR INDUSTRIAL REFRIGERATION

**Sergiu Lionte, Dimitri Cuenot Delattre, Hugo du Moulinet d'Hardemare, Michel Risser, Simon Robert, Pierre Couturier, Myriam Harnafi**

Magnoric SAS, Duppigheim, 67120, France, sergiu.lionte@magnoric.com

## ABSTRACT

In the last decades stricter environmental regulations and the phase-out process of high-GWP refrigerants have regulated more and more the traditional vapor-compression cooling technology, driving the development of cleaner solid-state alternatives such as magnetic cooling.

In this paper, we present our last developments of a new architecture large-scale magnetic cooling unit specifically engineered for commercial refrigeration. The mutual collaboration of research and engineering efforts demonstrates our expertise in areas such as mechanical engineering, optimal magnetic field arrangement, Active Magnetic Regenerator (AMR) geometry, and magneto-hydraulic synchronization. We will show the evolution of this magnetic cooling unit from its conceptualization, guided by an Artificial Evolution-based multi-physics and multi-scale numerical model, to its realization through detailed CAD designs.

The prototype's technical specifications and the initial operational results will prove that magnetic cooling is a mature technology ready to meet the technical requirements of the cooling industry.

**Keywords:** magnetic cooling, magnetic cooling unit, active magnetic regenerator

**References:** Lionte, S., Risser, M. & Muller, C. (2021), A 15kW magnetocaloric proof-of-concept unit: Initial development and first experimental results, International Journal of Refrigeration, 122, pp. 256–265. DOI: 10.1016/j.ijrefrig.2020.09.019

**Acknowledgement:** This work has been partially financed by the EU research funding program Eurostars 3 - Call 4, Application ID 4110 - Developing revolutionary energy efficient Magnetocaloric Cooling Units (MCUs) for the refrigerant industry

# HIGH-EFFICIENCY REGENERATORS BASED ON LA(FE,MN,SI)$_{13}$-H

**Edmund Lovell**[(a)], **Paul Burdett**[(a)], **Neil Wilson**[(a)]
[(a)] Camfridge Ltd, Milton Keynes, MK2 3HU, UK, elovell@camfridge.com

## ABSTRACT

Gadolinium remains a costly and critical material, still widely used in magnetic cooling systems.

This work presents a scalable, Gd-free alternative using high-power-density regenerators composed entirely of La(Fe,Mn,Si)$_{13}$-H alloys. Developed through a multi-year effort, these regenerators feature regular geometries delivering low pressure, and multi-material layering, optimized via a state-of-the-art characterization platform.

The resulting regenerator design achieves high operating frequency over a wide temperature span, enabling a compact cooling system that seamlessly integrates into commercial appliances, whilst boosting appliance efficiency (+25%) versus gas compression technology. Testing up to 3 Hz and 1 T demonstrates a near- proportional cooling power increase with frequency, reaching 456 W/kg and 182 W/kg for temperature spans of 0 K and 15 K, respectively – significantly enhanced compared to recently reported Gd-based cooling systems (e.g. Magnotherm Polaris in Liang, 2026).

With scalable production and competitive cost projections, this breakthrough in regenerator design enables commercially competitive magnetic cooling.

**Keywords:** magnetocaloric regenerator, magnetic cooling device, La(Fe,Mn,Si)$_{13}$-H, gadolinium-free

**References:** Liang J, Pickett J, Hermann S, et al. (2026) ‘Polaris: from laboratory prototypes to market-ready sustainable magnetic beverage coolers’, Appl. Therm. Eng., 284, 129144

# DESIGN AND OPTIMISATION OF A COMPACT MAGNETIC COOLING UNIT FOR COMMERCIAL REFRIGERATION

**Hugo du Moulinet d'Hardemare, Michel Risser, Sergiu Lionte, Simon Robert, Pierre Couturier**

[(a)] Magnoric SAS, Duppigheim, 67120, France, sergiu.lionte@magnoric.com

## ABSTRACT

This paper presents an improved design of a compact magnetocaloric unit developed by magnoric, which features an innovative hydraulic distribution system as well as a rotating longitudinal arrangement of Active Magnetic Regenerators. This design enables a better power density in a way that the MRS unit to be effectively integrated into a commercial refrigerated display cabinet for commercial use.

The prototype incorporates a fixed rectangular shaped magnetic system with NdFeB permanent magnets, and employs rotating beds with Gd-based alloys as the magnetocaloric materials.

The focus of this paper is on the improved architecture as well as on the description of the main components. The design process began with a series of numerical simulations using a previously introduced model, enhanced by an Evolutionary Algorithm (EA). This was followed by the CAD design of several essential components. Afterwards, we conducted and analyzed a set of experimental measurements on the complete system.

**Keywords:** magnetic cooling, magnetic cooling unit, active magnetic regenerator

**References:** Lionte, S., Risser, M., du Moulinet d'Hardemare, H. (2024), Successful integration of a magnetic refrigeration system into a refrigerated display cabinet: from simulations to first experimental results, 10th IIR International Conference on Caloric Cooling and Applications of Caloric Materials, Baotou, China. DOI: 10.18462/iir.thermag.2024.0009

# HOW ONE PROTOTYPE IS SHAPING NEXT-GENERATION MAGNETIC REFRIGERATORS

**Stefano Dall'Olio**

EFC Mag, Vipava, 5271, Slovenia, efcmag.cool@gmail.com

## ABSTRACT

Magnetic refrigeration is rapidly advancing from a promising concept to the most realistic alternative to vapor-compression systems, offering a practical path toward sustainable, high-efficiency cooling.

Building on MagQueen (Dall'Olio et al., 2021)—one of the highest-performing magnetic refrigeration prototypes developed to date (Masche et al., 2021,2022, 2023)—we now present a new TRL-4 prototype designed to accelerate the transition from research to real-world applications. This system is the most compact of its category and demonstrates how magnetic refrigeration can be effectively integrated into small-scale appliances.

Its key innovation is a patent-pending fluidic system that delivers higher efficiency, improved stability, and greater reliability, while using simplified, cost-effective components. The architecture is engineered to be robust yet easy to scale, supporting future development of larger and more powerful magnetic refrigeration products.

This work outlines the main features of this high-efficiency prototype and the roadmap guiding its evolution from laboratory innovation toward commercially viable cooling solutions.

**Keywords:** magnetic refrigeration, efficient cooling, innovative cooling.

**References:**

Dall'Olio, S. et al. (2021) 'Novel design of a high efficiency multi-bed active magnetic regenerator heat pump', International Journal of Refrigeration, 132, pp. 243–254. doi: 10.1016/j.ijrefrig.2021.09.007.

Masche, M. et al. (2021a) 'Performance analysis of a high-efficiency multi-bed active magnetic regenerator device', Applied Thermal Engineering, 199, article 117569. doi: 10.1016/j.applthermaleng.2021.117569.

Masche, M. et al. (2021b) 'Improving magnetic cooling efficiency and pulldown by varying flow profiles', Applied Thermal Engineering, 215, article 118945. doi: 10.1016/j.applthermaleng.2022.118945.

Masche, M. et al. (2023) 'Efficient modulation of the magnetocaloric refrigerator capacity', International Journal of Refrigeration, 145, pp. 59–67. doi: 10.1016/j.ijrefrig.2022.10.005.

# TERBIUM – A MAGNETOCALORIC MATERIAL OF THE EXTREME

**Tino Gottschall[(a)], Michael D. Kuz'min[(b)], Eduard Bykov[(a)], Marc Strassheim[(a,c)], Timo Niehoff[(a,c)], Catalina Salazar Mejía[(a)]**

[(a)] Dresden High Magnetic Field Laboratory (HLD-EMFL), Helmholtz-Zentrum Dresden-Rossendorf, Dresden, 01328, Germany, t.gottschall@hzdr.de

[(b)] Aix-Marseille Université, IM2NP, UMR CNRS 7334, Marseille, 13397, France

[(c)] Institut für Festkörper- und Materialphysik, TU Dresden, Dresden, 01069, Germany

## ABSTRACT

The rare-earth element gadolinium is considered the benchmark material for magnetic cooling because it's Curie temperature is located at room temperature (Gottschall et al., 2019). This circumstance and its extraordinary magnetocaloric properties are the reason why gadolinium is the most commonly used material in demonstrators around the world (Greco et al., 2019). In this work, we demonstrate that the rare-earth element terbium is even more astonishing in various ways. In direct pulsed fields measurements up to 62 T (Salazar Mejía et al., 2023), terbium shows a temperature change of about 73 K. Due to the asymmetry of the magnetocaloric peak in high fields, terbium is even superior to gadolinium in magnetic fields of more than 20 T at room temperature, despite its low Néel temperature of 233 K. Terbium also exhibits one of the highest magnetocrystalline anisotropies, making this element exciting for the rotary magnetocaloric effect. We present our direct measurements, which further highlight the outstanding nature of this element.

**Keywords:** magnetocaloric, materials, rare earths, pulsed magnetic fields, direct measurements

**References:**

Gottschall, T., Kuz'min, M.D., Skokov, K.P., Skourski, Y., Fries, M., Gutfleisch, O., Zavareh, M.G., Schlagel, D.L., Mudryk, Y., Pecharsky, V. and Wosnitza, J. (2019) Phys. Rev. B, 99, article 134429.

Greco, A., Aprea, C., Maiorino, A. and Masselli, C. (2019) Int. J. Refrig., 106, p. 66.

Salazar Mejía, C., Niehoff, T., Straßheim, M., Bykov, E., Skourski, Y., Wosnitza, J. and Gottschall, T. (2023) J. Phys. Energy, 5, article 034006.

**Acknowledgement:** This work was supported by the Clean Hydrogen Partnership and its members within the framework of the HyLICAL project (Grant No. 101101461) and the HLD at HZDR, member of the European Magnetic Field Laboratory (EMFL).

# MULTIFUNCTIONAL HIGH ENTROPY ALLOYS FOR CALORIC APPLICATIONS

**Vincent Fournée[a*], Dany Sihom Kwekam[a], Gwladys Lengaigne[a], Julian Ledieu[a], Jules Valentin[a], Pascal Boulet[a], Sylvie Migot[a], Jaafar Ghanbaja[a], Sorour Semsari Parapari[b], Saso Šturm[b], Simone Fabbrici[c], Lorenzo Gallo[c], Francesco Cugini[c], Massimo Solzi[c], Franca Albertini[c]**

[a] Institut Jean Lamour, CNRS-Université de Lorraine,
Nancy, 54011, France, vincent.fournee@univ-lorraine.fr

[b] Jozef Stefan Institute, Department for Nanostructured Materials, Ljubljana, 1000, Slovenia.

[c] Institute of Materials for Electronics and Magnetism (IMEM), National Research Council (CNR), Parma, 43124, Italy

[d] Department of Physics, University of Parma, Parma, 43124, Italy.

## ABSTRACT

High-entropy alloys (HEAs) mix five or more elements at near-equal concentration forming an ideal solid solution stabilized by a high mixing entropy. The huge compositional space of HEAs offers opportunities to discover new functional materials with improved properties. Inspired by recent reports, we present new results on the structure and magnetocaloric performances of some FeMnNiGeSi and FeMnNiCoGeSi HEAs. STEM indicates a perfect solid solution in the post-annealed samples, where all atomic species randomly occupy each crystallographic site. The magnetization curves M(H) reveal magnetic hysteresis at temperatures close to the transition reflecting a field induced first-order transition. We investigate the effect of chemical doping, demonstrating the possibility to tune the transition towards room temperature. The magnetocaloric effect is evaluated. Isothermal entropy change as large as about 40 $J.kg^{-1}.K^{-1}$ is attained at 5 T, while the thermal hysteresis is also reduced down to 7 K upon stress relief.

**Keywords:** Magnetocaloric effect, High-entropy alloys, Crystal structure, First-order magnetostructural transition, Room temperature magnetic refrigeration

**References:**

Guo, Y., Zhang, T., Zhang, Z., Chen, B. et al. (2022) ‘Large reversible magnetocaloric effect in high-entropy MnFeCoNiGeSi system with low-hysteresis magnetostructural transformation’, APL Mater., 10, pp. 091107. /10.1063/5.0108367

Han, L., Zhu, S., Rao, Z. et al. (2024) ‘Multifunctional high-entropy materials’, Nat Rev Mater, 9, pp. 846–865. /10.1038/s41578-024-00720-y.

Law, J.Y., Díaz-García, Á., Moreno-Ramírez, L.M., Franco, V. (2021) ‘Increased magnetocaloric response of FeMnNiGeSi high-entropy alloys’, Acta Materialia, 212, pp. 116931, /10.1016/j.actamat.2021.116931.

# DISENTANGLING CONVENTIONAL, ANISOTROPIC, STRUCTURAL, AND ELECTRONIC CONTRIBUTIONS TO THE MAGNETOCALORIC EFFECT IN MULTIFUNCTIONAL MAGNETIC MATERIALS

**Konstantin Skokov, Alex Aubert, Wei Liu, Benedikt Beckmann, Yulia Klunnikova, Oliver Gutfleisch**

Institute of Materials Science, Technical University of Darmstadt, Darmstadt, 64287, Germany,
Konstantin.Skokov@tu-darmstadt.de

## ABSTRACT

Multifunctional materials exhibiting strong coupling among structural, magnetic, and electronic degrees of freedom are central to next-generation solid-state refrigeration technologies. In systems with first-order phase transitions, external fields induce abrupt changes whose microscopic mechanisms remain insufficiently understood. We present an integrated approach to disentangle the interactions between these coupled subsystems and to elucidate the origins of the magnetocaloric effect and thermal hysteresis. Custom-built experimental setups enable simultaneous measurements of magnetization, magnetostriction, resistivity, and temperature under controlled thermodynamic conditions. Applied to benchmark materials such as $La(Fe,Si)_{13}$, Heusler alloys, FeRh, and $RCo_2$, these experiments allow quantitative evaluation of elastic and magnetoelastic couplings governing phase transformations. Complementary mean-field analysis of the data reveals the respective contributions of magnetic anisotropy, lattice distortions, and electronic degrees of freedom to the overall magnetocaloric response.

**Keywords:** Multicaloric effect, Scientific instrumentation, Mean-field theory, First-order transitions, Magnetic hysteresis

**References:** Skokov, K. P. (2023). Appl. Phys. Rev. 10, 031408 (doi: 10.1063/5.0133411); Aubert, A. (2024). ACS Appl. Mater. Interfaces, 16, 62358 (doi: 10.1107/S1600577524011718); Klunnikova, Y. (2025). Science and Technology of Advanced Materials,26 (1) 2517528. (doi: 10.1080/14686996.2025.2517528)

**Acknowledgement:** This work was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), Project ID No. 405553726, TRR 270.

# PHASE TRANSITIONS AND CALORIC EFFECTS IN $HF_{0.84}TA_{0.16}FE_2$

**Sven Wiesekopsieker[(a,b)], Tapas Samanta[(a)], Francesco Cugini[(c)], Luana Caron[(a,b)]**

[(a)] Faculty of Physics, Bielefeld University, Bielefeld 33501, Germany

[(b)] Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin 12489, Germany

[(c)]Department of Mathematical, Physical and Computer Sciences, Università di Parma, Parma 43121, Italy

lcaron@uni-bielefeld.de

## ABSTRACT

Ta-substituted $Fe_2Hf$ has been recently explored for its magnetocaloric properties aiming at cooling applications (Samanta et al., 2025), (Shen et al., 2026). $Hf_{0.84}Ta_{0.16}Fe_2$ exhibits an isosymmetric transition from a low-temperature ferromagnetic to a high-temperature antiferromagnetic state at $T_C = 262$ K , followed by a second-order transition to the paramagnetic state at $T_N = 321$ K . The first-order transition shows remarkably high magnetic field ($dT_C/dB$» 9 $K/T$) and pressure ($dT_C/dP$» − 9.8 K/kbar) sensitivities making it interesting from a fundamental viewpoint in the context of a limiting case as presented by Sandeman (Sandeman, 2012). In this work we will present a detailed study of the magnetocaloric effect in $Hf_{0.84}Ta_{0.16}Fe_2$ in ambient conditions using both direct and indirect methods as well as the influence of pressure on the magnetocaloric performance giving emphasis to the field-exponent $\eta$ of the entropy change $\Delta S \propto (\mu_0 H)^\eta$ (Law et al., 2018). We find that the ferro-antiferro transition becomes more first order with increasing pressure, increasing thermal hysteresis but also the entropy change.

**Keywords:** magnetocaloric, barocaloric, first-order

**References:**

Law, J.Y. et al. (2018) Nature Communications, 9, article 2680.

Samanta et al. (2025) APL Materials, 13, article 031112.

Sandeman (2012) Scripta Materialia, 67, p. 566.

Shen et al. (2026) Journal of Materials Science & Technology, 254, p. 196.

**Acknowledgement:** This work was carried out in the framework of the Joint Lab BiBer.

# MODELING THE MAGNETOCALORIC BEHAVIOR OF $HO_{1-X}ER_XAL_2$ WITHIN A MEAN-FIELD FRAMEWORK

**Bruno de P. Alho[a], Paula de O. Ribeiro[a], Rodrigo S. de Oliveira[a], Eduardo P. Nóbrega[a], Vinicius S. R. de Sousa[a], Pedro J. von Ranke[a]**

[a] Instituto de Física Armando Dias Tavares, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, 20550-013, Brazil, brunoalho@gmail.com.

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## ABSTRACT

We investigate magnetic, thermal, and magnetocaloric properties of rare earth intermetallic compounds $Ho_{1-x}Er_xAl_2$ with $x$ = 0, 0.05, 0.10, 0.20 and 0.25, through a theoretical model Hamiltonian that considers contributions of the crystalline electric field anisotropy in both Ho and Er magnetic sublattices, disorder in exchange interactions among Ho-Ho, Er-Er and Ho-Er magnetic ions, and the Zeeman effect.

M. Khan *et. al.* earlier reported (Khan et al., 2012) experimental measurements, we first determine a single free variable, the intersublattice magnetic exchange parameter, to properly model the temperature and magnetic field dependencies of heat capacity and magnetization. Then we used the modeling results to explain the emergence of a spin reorientation transition, how does it go from first to second order, and its influence on the magnetocaloric effect in the title compounds. Theoretical results agree with experimental data reasonably well.

**Keywords:** heat capacity; magnetocaloric effect; intermetallic compound.

**References:**

Khan, M., Gschneidner, K.A. and Pecharsky, V.K. (2012) 'The effect of Er doping on the spin reorientation transition in Ho1-xErxAl2', Journal of Magnetism and Magnetic Materials, 324, pp. 1381–1384. doi: 10.1016/j.jmmm.2011.11.045

**Acknowledgement:** Rio de Janeiro State University acknowledges financial support from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001, CNPq – Conselho Nacional de Desenvolvimento Científico e Tecnológico – Brazil and FAPERJ - Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro.

*ORAL PRESENTATIONS*

## S03 Magnetocalorics & Thermomagnetics LINHART HALL

Chair **Anja Waske** · Co-chair **Jia Yan Law** · Help **Jorge Revuelta Losada**

14:30 Modeling magnetic and magnetocaloric behaviour of ferromagnets with structural phase transitions
**Anna Kosogor** · *Univ. of Vienna · Krems · V.G. Baryakhtar Inst. of Magnetism*

14:42 3D-printed magnetocaloric regenerators: bridging design, materials, and functional performance
**Franziska Scheibel** · *TU Darmstadt*

14:54 Additive manufacturing of Heusler-type NiMn-based heat exchangers for magnetic refrigeration
**Daniel Salazar** · *BCMaterials, Basque Center for Materials*

15:06 Ultralow-cost magnetocaloric compound for cryogenic cooling
**Konstantin Skokov** · *TU Darmstadt*

15:18 Assessing the usability of mono- and polycrystalline holmium for magnetocaloric hydrogen liquefaction
**Massimo Solzi** · *University of Parma*

15:30 Superconducting magnetic systems for magnetocaloric hydrogen liquefaction
**Clara Estillac Leal Silva** · *Helmholtz-Zentrum Dresden-Rossendorf*

15:42 Modeling and scaling of ADR systems for next-generation millikelvin cooling for quantum computers
**Rajat Arunachala Chandavar** · *kiutra GmbH*

15:54 The development of a cryogenic magnetocaloric cooling device for the liquefaction of hydrogen
**Thomas Platte** · *Magnotherm Solutions GmbH*

16:06 Performance assessment of layered active magnetic regenerators in cryogenic hydrogen liquefaction
**Afshin Mashayekh** · *Technical University of Denmark (DTU)*

16:18 Surveying different magnetocaloric materials using an active magnetic regenerative regenerator (AMRR) for hydrogen liquefaction
**Mohamed Gado** · *National Institute for Materials Science*

# MODELING MAGNETIC AND MAGNETOCALORIC BEHAVIOR OF FERROMAGNETS WITH STRUCTURAL PHASE TRANSITIONS

**Anna Kosogor[a,b,c], Olga Salyuk[c], Victor A. L'vov[c]**

[a] University of Vienna, Faculty of Physics, Vienna, 1090, Austria, anna.kosogor@univie.ac.at

[b] University for Continuing Education Krems, Wiener Neustadt, 2700, Austria

[c] V.G. Baryakhtar Institute of Magnetism of the NAS of Ukraine, Kyiv, 03142, Ukraine, victor.a.lvov@gmail.com

## ABSTRACT

The giant magnetocaloric effect is often linked to first-order magnetostructural transitions involving both magnetic and structural changes. To describe this behavior, a thermodynamic analysis of ferromagnets undergoing structural phase transitions (SPTs) near the Curie temperature is presented. The study considers the influence of SPTs on the magnetic energy and introduces a quasi-first-order phase transition model assuming a sharp temperature dependence of the spin-exchange energy near the Curie point (L'vov et al., 2025). This dependence arises from the relative displacement of magnetic atoms at different crystallographic sites, coupling magnetic and structural degrees of freedom. The applicability of the model is confirmed by the quantitative agreement between the calculated and experimental temperature dependences of magnetization and specific heat for Heusler ferromagnetic alloys undergoing SPTs. Using general thermodynamic relations, the model estimates field-induced entropy and adiabatic temperature changes, both showing strong dependence on the temperature difference between the structural transition and the Curie point.

**Keywords:** Magnetic energy; magnetization; heat capacity; magnetocaloric effect; adiabatic temperature change.

**References:**

L'vov, V.A., Salyuk, O. and Kosogor, A. (2025) 'Thermodynamic analysis of magnetocaloric properties of ferromagnet undergoing structural phase transition near Curie temperature', Scientific Reports, 15, article 31002. doi: 10.1038/s41598-025-15896-8.

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# 3D-PRINTED MAGNETOCALORIC REGENERATORS: BRIDGING DESIGN, MATERIALS, AND FUNCTIONAL PERFORMANCE

**Franziska Scheibel[(a)], Sagar Ghorai[(a)], David Zentgraf[(b)], Jens-Peter Zwick[(c)], Dimitri Benke[(c)], Oliver Gutfleisch[(a)]**

[(a)] Institute of Materials Science, Technical University of Darmstadt, Darmstadt, 64287, Germany, franziska.scheibel@tu-darmstadt.de

[(b)] Institute for Production Management, Technical University of Darmstadt, Darmstadt, 64287, Germany

[(c)] MAGNOTHERM Solutions GmbH, Darmstadt, 64297, Germany

## ABSTRACT

Additive manufacturing (AM) enables the fabrication of magnetocaloric regenerators with complex geometries, optimizing thermal exchange and minimizing pressure drop in magnetic cooling devices. Using laser powder bed fusion (PBF-LB), net-shape parts can be produced from materials that are otherwise difficult to process, such as gadolinium. The flexibility of PBF-LB allows rapid adaptation of microchannel designs and outer geometries, facilitating accelerated development from material to device level.

This study presents the complete processing chain from Gd powder to fully functional, net-shaped regenerators. Structural and functional characterization includes the magnetocaloric effect, pressure drop analysis of complex structures, achieved temperature span, and performance evaluation in a real magnetocaloric refrigerator (POLARIS©, MAGNOTHERM Solutions). The work highlights key challenges and advantages across the processing chain, including powder availability, processability, and depowdering, providing valuable insights for the advancement of additively manufactured caloric materials and devices.

**Keywords:** Additive Manufacturing, magnetocalorics, Net-shaped regenerator, 3D Design Optimization, Process–Structure–Property Relationship

**References:**

Gottschall, T. et al. (2019) *Advanced Energy Materials*, 9, article 1901322. doi: 10.1002/aenm.201901322.

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# ADDITIVE MANUFACTURING OF HEUSLER-TYPE NIMN-BASED HEAT EXCHANGERS FOR MAGNETIC REFRIGERATION

**Daniel Salazar**[(a)]

[(a)] BCMaterials, Basque Center for Materials, Applications and Nanostructures, EHU Science Park Leioa, 48940, Spain, daniel.salazar@bcmaterials.net

## ABSTRACT

Addressing current societal challenges requires eco-friendly technologies and sustainable, profitable routes for manufacturing three-dimensional structures. Caloric materials are central to next-generation energy-efficient devices and create opportunities for additive manufacturing. Metamagnetic shape-memory alloys are attractive for magnetic refrigeration because their first-order martensitic transformation produces a large entropy change; however, their crystalline phase becomes unstable above ~300 °C, which constrains conventional thermal processing. In this work, we formulate printable inks and pastes for screen-printing and direct-ink-writing to fabricate complex 3D architectures from NiMn-based powders developed via alloy design. A sustainable binder system of hydroxypropyl-cellulose in deionized water is employed. The inks contain >95 wt.% powder and are rheologically optimized to enable deposition of hundreds of layers with high fidelity (~0.5mm wall thickness). Post-processing comprises controlled drying, polymer removal by calcination, and sintering to obtain fully metallic structures, followed by Ni-electrodeposition to enhance corrosion resistance. The resulting solid sections exhibit <8 vol.% porosity.

**Keywords:** Additive Manufacturing, Metamagnetic Shape Memory Alloys, Heat-Exchangers, Magnetocalorics

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# ULTRALOW-COST MAGNETOCALORIC COMPOUND FOR CRYOGENIC COOLING

**Wei LIU[(a)], Benjamin Theisel[(a)], Yuila Klunnikova[(a)], Konstantin Skokov[(a)], Oliver Gutfleisch[(a)]**

(a) Materials Science, TU Darmstadt Darmstadt, 64287, Germany, wei.liu@tu-darmstadt.de

## ABSTRACT

The search for cost-effective magnetocaloric materials is essential for large-scale cryogenic applications such as hydrogen liquefaction (Liu et al., 2022,2024).We report the ionic compound $FeCl_2$, composed entirely of earth-abundant elements, as a promising non-rare-earth magnetocaloric material. $FeCl_2$ exhibits both inverse and conventional magnetocaloric effects related to an antiferromagnetic transition near 24 K and a field-induced spin-flip transition around 1.5 T. The conventional magnetic entropy change reaches 18.6 J /kg /K at 5 T, comparable to heavy rare-earth materials like $DyNi_2$. The adiabatic temperature change $\Delta T_{ad}$ attains 3.6 K under 5 T. Combined with its ultralow material cost and scalability from $FeCl_2 \cdot 4H_2O$ precursors, $FeCl_2$ represents a new class of sustainable ionic compounds for magnetocaloric hydrogen liquefaction in the 20–77 K range.

**Keywords:** magnetocaloric effect, hydrogen liquefaction, cryogenic cooling, antiferromagnetism

**References:**

Liu, W. et al. (2022) Applied Materials Today, 29, article 101624. doi: 10.1016/j.apmt.2022.101624.

Liu, W. et al. (2024) Journal of Alloys and Compounds, 995, article 174612. doi: 10.1016/j.jallcom.2024.174612.

**Acknowledgement:** This work is supported by the Clean Hydrogen Partnership and its members within the framework of the project HyLICAL (Grant No. 101101461)

# ASSESSING THE USABILITY OF MONO- AND POLYCRYSTALLINE HOLMIUM FOR MAGNETOCALORIC HYDROGEN LIQUEFACTION

**Massimo Solzi[a][*], Francesco Cugini[a], Lara Righi[b], Eleonora Gadducci[c], Maurizio Vaccaro[c], Alessandra Giannasi[d]**

[a] Department of Mathematical, Physical and Computer Sciences, University of Parma, Parco Area delle Scienze 7/A, I-43124, Parma, Italy

[b] Department of Chemical Sciences, Life and Environmental Sustainability, University of Parma, Parco Area delle Scienze 17/A, I-43124, Parma, Italy

[c] Nuovo Pignone International, Via Felice Matteucci 2, I-50127, Firenze, Italy

[d] Nuovo Pignone Tecnologie, Baker-Hughes, Via Felice Matteucci 2, I-50127, Firenze, Italy

(*) corresponding author: email massimo.solzi@unipr.it; phone +39 0521 905242

## ABSTRACT

Magnetic refrigeration using magnetocaloric materials offers a promising, eco-friendly method for hydrogen liquefaction (Kitanovski, 2020; Wang, 2025), potentially surpassing 60% Carnot efficiency. Its success depends on materials with strong magnetocaloric effects between 20 K and 77 K, with Holmium representing an interesting option (Terada, 2021). In this work we provide a complete magnetic and magnetocaloric characterization of both single crystalline, along three crystallographic orientations, and polycrystalline Holmium in view of its potential application in magnetocaloric hydrogen liquefaction devices. The complex magnetic phase diagram of Holmium (Zverev, 2015) has been thoroughly analyzed within the region of application, considering the typology of phase transitions. Holmium polycrystals exhibit magnetocaloric properties comparable to single crystals, but with reduced anisotropy-related challenges. Unlike single crystals, polycrystals simplify device design minimizing mechanical stress from magnetic forces. Finally, we investigated the impact of material shaping and processing techniques on the magnetic and magnetocaloric properties of polycrystalline Holmium.

**Keywords:** magnetocaloric effect, magnetic cooling, hydrogen liquefaction, Holmium, direct adiabatic temperature change measurements

**References:**

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Terada, N. and Mamiya, H. (2021) 'High-efficiency magnetic refrigeration using holmium', *Nature Communications*, 12, article 1212. doi: 10.1038/s41467-021-21234-z.

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Zverev, V.I. et al. (2015) 'Magnetic and magnetothermal properties, and the magnetic phase diagram of single-crystal holmium along the easy magnetization direction', *Journal of Physics: Condensed Matter*, 27, article 146002. doi: 10.1088/0953-8984/27/14/146002.

**Acknowledgement:** This work received financial support from Nuovo Pignone Tecnologie S.r.l. in the framework of a project financed by PNRR PE0000021 "NEST - Network 4 Energy Sustainable Transition" CUP B13D22001280004.

# SUPERCONDUCTING MAGNETIC SYSTEMS FOR MAGNETOCALORIC HYDROGEN LIQUEFACTION

**Clara Estillac Leal Silva[a,b], Thomas Platte[d], Marc Straßheim[a,c], Timo Niehoff[a,c], Catalina Salazar-Meija[a], Tino Gottschall[a]**

(a) Dresden High Magnetic Field Laboratory (HLD-EMFL), Helmholtz-Zentrum Dresden-Rossendorf, Dresden, 01328, Germany, c.estillac-leal-silva@hzdr.de

[b]TU Bergakademie Freiberg, Freiberg, 09599, Germany

[c]Institut für Festkörper- und Materialphysik, TU Dresden, Dresden, 01069, Germany

[d]Magnotherm Solutions GmbH, Darmstadt, 64297, Germany

## ABSTRACT

The growing role of hydrogen in clean energy demands more efficient liquefaction methods, as its liquefied form offers high volumetric energy density for storage and transport. Conventional compression-based systems are costly and energy-intensive, motivating the exploration of magnetic refrigeration (Bracha et al., 1994). This approach employs the adiabatic temperature variation of magnetocaloric materials in an Active Magnetocaloric Regenerator to operate the final cooling stage for hydrogen liquefaction (Liu et al., 2024). Achieving large temperature spans demands high magnetic fields that can only be obtained using superconductors. Also, attaining high operating frequency and thus greater efficiency, requires a rotary configuration, involving a magnetic system capable of sustaining high fields while allowing rotational motion of the magnetocaloric material (Gottschall et al., 2024), (Barclay et al., 2018). We discuss our developments of superconducting magnetic systems meeting these requirements. The design is supported by finite element simulations of the field distribution and the magnetic forces involved, targeting a concentrated 5 T field enabling a sharp field change.

**Keywords:** Magnetocaloric Refrigeration, Hydrogen Liquefaction, Superconducting Magnets, Magnetic System.

**References:**

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**Acknowledgement:** This work was supported by the Clean Hydrogen Partnership and its members within the framework of the HyLICAL project (Grant No. 101101461) and the HLD at HZDR, member of the European Magnetic Field Laboratory (EMFL).

# MODELING AND SCALING OF ADR SYSTEMS FOR NEXT-GENERATION MILLIKELVIN COOLING FOR QUANTUM COMPUTERS

**P. Schüßler[(a)], R. Chandavar[(a)], A. Kinast[(a)], A. Wendl[(a)], J. Rothe[(a)], J. Spallek[(a)], S. Säubert[(a)*]**

[(a)] kiutra GmbH, Flößergasse 2, 81369 Munich, Germany, *steffen.säubert@kiutra.com

## ABSTRACT

Quantum technologies—especially superconducting quantum computing—require robust, scalable cooling deep in the millikelvin regime. Adiabatic Demagnetization Refrigeration (ADR) is a helium-3-free, modular technique capable of meeting these demands. Building on our earlier demonstration of continuous ADR (cADR) below 30 mK in a compact rack-mounted system (Schüßler et al., 2025), the present work advances this approach toward a larger-scale platform targeting 20 µW at 20 mK, far beyond the ~3 µW at 50 mK achieved previously. Reaching this performance necessitates a full redesign of ADR components and a detailed understanding of their coupled behaviour. We therefore developed an integrated modeling framework capturing the entire cADR cycle (Chandavar et al., 2025)—including refrigerants, mechanical and superconducting heat switches, and all thermal interfaces—and validated it experimentally using a dedicated millikelvin test system. The combined simulations and measurements reveal key insights into materials, interface conductance, and switching dynamics, guiding the optimization of next-generation, scalable magnetic refrigeration for quantum computing infrastructure.

**Keywords:** adiabatic demagnetization refrigeration (ADR); quantum computing; millikelvin cooling

**References:**

Chandavar, R.A., Schüßler, P. et al. (2025) 'Numerical modeling of adiabatic demagnetization refrigeration based on paramagnetic salt entropy properties', manuscript in preparation.

Schüßler, P. et al. (2025) 'A Compact Cryogen-Free continuous ADR Platform for Quantum Technology Applications', manuscript under review.

**Acknowledgement:** Funded by the European Innovation Council Pathfinder Challenge under the Grant agreement ID: 101161522, and the BMBF and Eurostars-2 joint program with co-funding from the European Union Horizon 2020 research and innovation program, FKZ01QE2113A.

# DEVELOPMENT OF A CRYOGENIC MAGNETOCALORIC COOLING DEVICE FOR THE LIQUEFACTION OF HYDROGEN

**Thomas Platte[(a)], Jierong Liang[(b)], Marc Straßheim[(b)], Christopher Fujta[(a)], Tim Sittig[(a)], Maximilian Fries[(a)], Allan Döring[(c)], Wei Liu[(c)], Konstantin Skokov[(c)], Franziska Scheibel[(c)] Oliver Gutfleisch[(c)], Tino Gottschall[(b)]**

[(a)] Magnotherm Solutions GmbH Darmstadt, 64297, Germany, platte@magnotherm.com

[(b)] Dresden High Magnetic Field Laboratory (HLD-EMFL), Helmholtz-Zentrum Dresden-Rossendorf Dresden, 01328, Germany

[(c)] Institute of Materials Science, Technical University of Darmstadt Darmstadt, 64287, Germany

## ABSTRACT

Hydrogen will play a central role as an energy carrier in the future (Liu et al., 2022). In its liquid state, hydrogen has enormous potential due to its high density, purity and easy handling during transport. However, the boiling point of hydrogen is only 20 K. Cryogenic magnetic refrigeration can be the key technology for liquefying hydrogen in an energy- and cost-efficient manner (Magnotherm). In this work, we present the design and the results of our reciprocating magnetocaloric demonstrator using a large-bore superconducting magnet with a maximum field of 19 T and the rare earth holmium as the refrigerant. Helium gas is used as the heat-exchange fluid. The hot heat exchanger is connected to a bath of liquid nitrogen to realize precooling down to 77 K. In our first experiments, we could establish a temperature span of 17 K in a 9 T field. These are the first promising steps towards Europe's first magnetic hydrogen liquefier.

**Keywords:** magnetocaloric, hydrogen, liquefaction, device

**References:**

Liu, W., Bykov, E., Taskaev, S., Bogush, M., Khovaylo, V., Fortunato, N., Aubert, A., Zhang, H., Gottschall, T., Wosnitza, J., Scheibel, F., Skokov, K. and Gutfleisch, O. (2022) Applied Materials Today, 29, article 101624. doi: 10.1016/j.apmt.2022.101624.

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# PERFORMANCE ASSESSMENT OF LAYERED ACTIVE MAGNETIC REGENERATORS IN CRYOGENIC HYDROGEN LIQUEFACTION

**Afshin Mashayekh[(a)(*)], Jierong Liang[(b)], Tino Gottschall[(b)], Rasmus Bjørk[(a)]**

[(a)] Department of Energy Conversion and Storage, Technical University of Denmark (DTU)
Anker Engelundsvej, 2800 Kgs. Lyngby, Denmark
[(b)] Helmholtz-Zentrum Dresden-Rossendorf (HZDR)
Bautzner Landstraße 400, 01328 Dresden, Germany (*) Corresponding author, email: afmas@dtu.dk

## ABSTRACT

An Active Magnetic Regenerative (AMR) system designed for hydrogen liquefaction is investigated in this study to determine how material layering influences its thermodynamic performance. Using a numerical AMR model accounting for the compressibility of the heat transfer fluid (Diamantopoulos et al., 2025), the analysis evaluates the cooling power and coefficient of performance (COP) as functions of the Curie temperature of the magnetocaloric materials, the fractional composition of the layers within the AMR bed, regenerator flow profile, and the mass flow rate of the helium as the heat transfer fluid. A systematic parametric study is conducted to identify optimal combinations for achieving the maximum cooling power. The results, validated by experiments from HZDR, reveal that employing layered magnetocaloric materials with properly selected Curie temperatures substantially improves both cooling power and COP compared to single-layer configurations. These findings contribute to the improved design and optimization of AMR-based hydrogen liquefaction systems.

**Keywords:** Active Magnetic Regenerative, Magnetocaloric Materials, Curie Temperature, Hydrogen Liquefaction, Cooling Power

**References:** Diamantopoulos, T., Moreno-Ramírez, L. M., Franco, V., & Bjørk, R. (2025). A fast 1D model of active magnetic regeneration with a compressible working fluid. International Journal of Refrigeration, 178, 359-366. https://doi.org/10.1016/j.ijrefrig.2025.07.005.2025.07.005

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# SURVEYING DIFFERENT MAGNETOCALORIC MATERIALS USING AN ACTIVE MAGNETIC REGENERATIVE REGENERATOR (AMRR) FOR HYDROGEN LIQUEFACTION

**Mohamed G. Gado, Tsuyoshi Shirai, Kyohei Natsumi, Akira Uchida, Takenori Numazawa, Koji Kamiya**

National Institute for Materials Science Tsukuba, 305-0003, Japan, mohamed.gado@nims.go.jp

## ABSTRACT

Hydrogen serves as a key clean energy carrier for decarbonization. Liquefied hydrogen offers high volumetric energy density for efficient storage and transport. However, its low liquefaction temperature of 20 K makes the process energy-intensive (Numazawa et al., 2014). This study investigates magnetic refrigeration as a potential method to enhance hydrogen liquefaction efficiency. Utilizing the magnetocaloric effect (MCE), magnetic refrigeration enables an efficient cooling cycle, which reduces energy consumption in the liquefaction process (Kamiya et al., 2025). Herein, granular $HoAl_2$ particles have been proposed, given their significant specific heat and strong MCE. To boost the temperature span, an Active Magnetic Regenerative Refrigerator (AMRR) is deployed (Barclay et al., 1982), (Holladay et al., 2018). Helium (instead of hydrogen gas) is used as a process gas to abate hydrogen embrittlement. In the present study, different magnetocaloric materials have been utilized to examine the hydrogen liquefaction efficiency in comparison to $HoAl_2$. This will eventually upgrade hydrogen utilization and push boundaries toward achieving a hydrogen society.

**Keywords:** Magnetic refrigeration, Hydrogen liquefaction, strong MCE

**References:**

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Holladay, J., Teyber, R., Meinhardt, K., Polikarpov, E., Thomsen, E., Archipley, C. et al. (2018) Cryogenics, 93, pp. 34–40. doi: 10.1016/j.cryogenics.2018.05.010.

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Numazawa, T., Kamiya, K., Utaki, T. and Matsumoto, K. (2014) 'Magnetic refrigerator for hydrogen liquefaction', Cryogenics, 62, pp. 185–192. doi: 10.1016/j.cryogenics.2014.03.016.

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## S04 Electrocalorics & Pyroelectrics KOSOVEL HALL

Chair **Hana Uršič** · Co-chair **Morgan Almanza** · Help **Izak Oberčkal Pluško**

14:30 The perspectives of ultra-high-temperature solid-state heat pumps
**Katja Klinar** · *FME, University of Ljubljana*

14:42 Lead-free materials for electrocaloric cooling
**Emmanuel Defay** · *LIST*

14:54 Efficient 1000 V antiphase charging of two capacitors for electrocaloric cooling using SiC half-bridge converter
**Stefan Mönch** · *University of Stuttgart*

15:06 A generalized modelling approach for active electrocaloric regenerators
**Matija Kalin** · *FME, University of Ljubljana*

15:18 Polymer architectures for next-generation electrocaloric cooling
**Nishchay Saurabh** · *Luxembourg Institute of Science and Technology*

15:30 Ceramic multilayer components for application in electrocaloric systems
**Christian Molin** · *Fraunhofer IKTS Dresden*

15:42 Lead scandium tantalate thick films fabricated by powder aerosol deposition
**Matteo D'Angelo** · *Jožef Stefan Institute, Ljubljana*

15:54 Landau approach for pyroelectric energy harvesting in ferroelectrics
**Gaspard Taxil** · *Luxembourg Institute of Science and Technology*

16:06 Electrocaloric and energy storage properties of Mn-doped $(1-x)Pb(Fe_{0.5}Nb_{0.5})O_3 - xBiFeO_3$ ceramics
**Ivana Goričan** · *Jožef Stefan Institute*

# THE PERSPECTIVES OF ULTRA-HIGH-TEMPERATURE SOLID-STATE HEAT PUMPS

**Katja Klinar[(a)], Darja Gačnik[(a)], Radel Gimaev[(a)], Andrej Kitanovski[(a)]**

[(a)] Faculty of Mechanical Engineering, University of Ljubljana Ljubljana, 1000, Slovenia, katja.klinar@fs.uni-lj.si

## ABSTRACT

Conventional heat pump technologies are well suited for low- and medium- temperature sources, but not for ultra-high temperatures above 300 °C. This presentation will highlight the opportunities and challenges for emerging and environmentally friendly high temperature heat pump technologies based on solids (Kitanovski et al., 2025). These technologies have the potential to deliver heat at temperatures of up to 1,600 K. Solid-based high-temperature heat pumps offer the advantages of using solid refrigerants that eliminate the risk of leakage and have recycling potential. Technologies such as magnetocaloric, electrocaloric (Klinar et al., 2026), mechanocaloric, and thermoelectric (Peltier) are based on different solid-state phenomena. In this presentation, each of these technologies will be presented in more detail: we will give an outlook on possible solutions, applications, scalability, and a roadmap for future technological advances.

**Keywords:** magnetocaloric, electrocaloric, mechanocaloric, thermoelectric, heat transfer, refrigeration, heat pump, high temperature, solid-state

**References:**

Kitanovski, A., Klinar, K., Luo, E. et al. (2025) 'Emerging opportunities for high-temperature solid-state and gas-cycle heat pumps', Nature Energy, 10, pp. 1412–1426. doi: 10.1038/s41560-025-01908-4.

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# LEAD FREE MATERIALS FOR ELECTROCALORIC COOLING

**Junning Li[(a)], Veronika Kovacova[(a)], Longfei Song[(a)], Youri Nouchokgwe[(a)], Torsten Granzow[(a)], Sakyo Hirose[(b)], and Emmanuel Defay[(a,c)]**

[(a)] Luxembourg Institute of Science and Technology, Esch-sur-Alzette, Luxembourg.

[(b)] Murata Manufacturing Co., Ltd., Higashikotari 1, Nagaokakyo, Kyoto, 617–8555, Japan.

[(c)] University of Luxembourg, Esch-sur-Alzette, Luxembourg, * emmanuel.defay@list.lu

## ABSTRACT

Among electrocaloric materials, barium titanate (BTO) and its derivatives have long served as benchmark systems due to their environmentally benign composition, though their electrocaloric performance has fallen short of that achieved by lead scandium tantalate ceramics with which the largest temperature span ever obtained on electrocaloric regenerators has been reached (20 K) (Li et al., 2023). However, these lead-based ceramics depend on scarce, toxic, or environmentally persistent elements.

In this work, we present the development of low-cost, lead-free, and eco-friendly manganese-doped barium strontium titanate multilayer capacitors, designed with an optimized architecture and fabricated via an industrially scalable process. These capacitors demonstrate an adiabatic electrocaloric temperature change beyond 2 K. When integrated into a regenerative cooling system, they achieve a temperature span at the same level as lead scandium tantalate, without electrical breakdown.

This work represents a substantial step toward sustainable electrocaloric cooling based on abundant, non-toxic materials and scalable manufacturing approaches.

**Keywords**: Electrocalorics – cooling – lead free

**References:** J Li, A Torelló, V Kovacova, U Prah, A Aravindhan, T Granzow, T Usui, S Hirose, E Defay, High cooling performance in a double-loop electrocaloric heat pump, Science 382 (6672), 801-805 (2023)

**Acknowledgement:** The Fonds National de la Recherche (FNR) of Luxembourg is acknowledged for supporting this work through the projects COOLISH.

# EFFICIENT 1000 V ANTIPHASE CHARGING OF TWO CAPACITORS FOR ELECTROCALORIC COOLING USING SIC HALF-BRIDGE CONVERTER

**Stefan Mönch[a,b], Ines Bennour[a], Adrian Söllner[a], Jan Schipper[a], Fabrice Domingues Dos Santos[c], Valerio Zerillo[d], Emmanuel Defay[e]**

[a] University of Stuttgart, Institute of Electrical Energy Conversion (IEW), Stuttgart, 70569, Germany, stefan.moench@iew.uni-stuttgart.de

[b] Fraunhofer Institute for Applied Solid State Physics IAF, Freiburg, 79110, Germany

[c] Arkema-Piezotech, Colombes, 92700, France

[d] KEMET Electronics Corporation, Borgonuovo BO, 40037, Italy

[e] Luxembourg Institute of Science and Technology (LIST), Esch-sur-Alzette, 4362, Luxembourg

## ABSTRACT

Scaling up electrocaloric cooling or heat pump systems requires a significant geometric volume and electrical capacitance resulting from the electrocaloric material. To realize high electrical fields (e.g., 100V/µm), required for high electrocaloric temperature changes in PVDF-based polymers, is a trade-off between layer thickness and operation voltage. While thin layers reduce the required voltage (e.g., below 400V), they also increase the fabrication effort, number of electrodes requires and add inactive thermal mass. Thus, efficient high voltage electronics is currently in the focus of research. While multilevel converters previously showed ultra-high electrical efficiencies at voltages up to around 400V, more simple two-level half-bridge converters might be preferred for lower-cost and simpler systems. This work demonstrates 1000V charging of two 5µF capacitors in antiphase using an around 98…99% efficient silicon carbide (SiC) based half-bridge converter with zero-voltage switching and hysteretic current control. Preliminary measurements charging/discharging electrocaloric polymers (COOLPOL project) will also be presented.

**Keywords:** Electrocalorics, DC-DC Converters, Energy Efficiency, Power Electronics

**References:** Mönch, S., Reiner, R., Basler, M., Mansour, K., Grieshaber, D. & Waltereit, P. et al. (2024) Progress on Power Electronics for Electrocaloric Heat Pump Systems. *10th IIR Conference on Caloric Cooling and Applications of Caloric Materials (Thermag 2024)*. https://doi.org/10.18462/IIR.THERMAG.2024.0023.

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# A GENERALIZED MODELLING APPROACH FOR ACTIVE ELECTROCALORIC REGENERATORS

**Matija Kalin[(a)], Darja Gačnik[(a)], Katja Klinar[(a)], Andrej Kitanovski[(a)]**
[(a)] University of Ljubljana, Faculty of Mechanical Engineering Ljubljana, 1000, Slovenija,
Andrej.Kitanovski@fs.uni-lj.si

## ABSTRACT

Caloric materials exhibit a reversible temperature change when exposed to an external field, offering an environmentally friendly alternative to traditional heat-pumping systems. Among them, electrocaloric materials are particularly attractive due to the ease of applying electric fields via electrodes (Torelló et al., 2022). However, their relatively small adiabatic temperature change limits practical applications (Valant et al., 2012). The temperature span of electrocaloric heat-pumping devices can be enhanced by implementing active regeneration (Kitanovski et al., 2015). Experimental prototypes have demonstrated the potential of this approach, but their designs require optimization (Plaznik et al., 2015, 2019), (Torelló et al., 2020). Numerical modelling provides an efficient pathway for this, given the large number of parameters influencing performance. Here, we present a generalized numerical modelling framework for electrocaloric active regenerators that allows easy modification of device geometry, materials, operating and boundary conditions, enabling systematic design optimization and performance prediction. A representative case study exploring various AER geometries, materials and operating conditions demonstrates the capabilities, effectiveness and advantages of the presented framework.

**Keywords:** Electrocaloric effect, active regeneration, numerical modelling, optimization

**References:**

Kitanovski, A. et al. (2015) 'Present and future caloric refrigeration and heat-pump technologies', International Journal of Refrigeration, 57, pp. 288–298. doi: 10.1016/j.ijrefrig.2015.06.008.

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**Acknowledgement:** The authors acknowledge the financial support of the Slovenian Research Agency for the research core funding no. P2-0223 Heat and Mass Transfer. This work was financially supported by the University of Ljubljana / Slovenian Research Agency as part of the Young Researcher PhD program

# POLYMER ARCHITECTURES FOR NEXT-GENERATION ELECTROCALORIC COOLING

**Nishchay Saurabh[(a)], Omar Ramirez Sanchez[(a)], Uros Prah[(a)], Fabrice Domingues Dos Santos[(b)], Stefan Mönch[(c)], Valerio Zerillo[(d)], Emmanual Defay[(a,e)]**

[(a)]Luxembourg Institute of Science and Technology, Smart Materials Unit, Esch-sur-Alzette, L-4362, Luxembourg, nishchay.saurabh@list.lu, omar.ramirez@list.lu, uros.prah@list.lu, emmanuel.defay@list.lu

[(b)]ARKEMA FRANCE SA, Colombes, 92700, France, fabrice.domingues-dos-santos@arkema.com

[(c)]University of Stuttgart, Stuttgart, 70569, Germany, stefan.moench@iew.uni-stuttgart.de

[(d)] KEMET ELECTRONICS ITALIA S.R.L., Sasso Marconi, 40037, Italy, valerio.zerillo@yageo.com

[(e)]University of Luxembourg, Department of Physics and Materials Science, Belvaux, L-4422, Luxembourg

## ABSTRACT

Refrigeration systems account for nearly 20% of global energy consumption, with the efficiency of conventional vapor-compression cooling limited to 40–60% (Dupont et al., 2019). The electrocaloric effect (ECE) has emerged as a promising pathway toward efficient, compact, and environmentally friendly solid-state cooling. This study investigates PVDF-based multilayer capacitors (MLCs) as electrocaloric cooling elements, offering light weight, mechanically flexible, and low-cost alternative as compared to conventional ceramics. A prototype comprising multiple vertically stacked MLCs with interlayer gaps and enclosed within a shrink tube, was fabricated. A low-viscous silicone oil was reciprocated through the gaps to enable effective heat transfer between the MLCs and the reciprocating fluid. The prototype operating at 50°C demonstrated a temperature span of 15.8°C at an applied voltage of 250 V, a flow rate of 37 mL/min and period of 7 s. These results highlight the strong potential of polymer-based MLC systems as sustainable and scalable alternatives to traditional cooling technologies.

**Keywords**: Electrocaloric, Cooling, Polymer, MLC

**References:** Dupont, J.L., Domanski, P., Lebrun, P. and Ziegler, F., 2019. The role of refrigeration in the global economy-38. Informatory Note on Refrigeration Technologies (No. INIS-FR--20-0278). International institute of refrigeration/Institut international du froid, 177, boulevard Malesherbes, 75017 Paris (France).

**Acknowledgement:** Project 101161087 — COOLPOL funded by the European Union.

# CERAMIC MULTILAYER COMPONENTS FOR APPLICATION IN ELECTROCALORIC SYSTEMS

**Christian Molin[(a)], Zhenglyu Li[(a)], Sylvia E. Gebhardt[(a)]**

[(a)] Fraunhofer Institute for Ceramic Technologies and Systems IKTS Dresden, 01277, Germany,
christian.molin@ikts.fraunhofer.de

## ABSTRACT

Ideally, electrocaloric (EC) materials should possess large temperature changes and low losses. Appropriate EC components should therefore exhibit high dielectric strength as well as a reasonable refrigerant volume. Most promising results are achieved with multilayer ceramic (MLC) components, showing an increased dielectric strength accompanied with low operational voltages and an easy-to-adjust component thickness.

We will give an overview of our work on EC material and component development. While 1-x $(Pb(Mg_{1/3}Nb_{2/3})O_3$ – x $PbTiO_3$ (PMN-PT) based MLCs show high dielectric strength and reasonable EC effect of up to $\Delta T$ = 2 K, microstructure of $Ba_{0.82}Sr_{0.18}Sn_{0.065}Ti_{0.935}O_3$ (BSSnT) ceramics had to be adjusted to avoid abnormal grain growth. We systematically modified material composition and prepared BSSnT MLCs showing $E_{\mathrm{BD}}$ = 30 V/µm and $\Delta T$= 1.4 K. Influence of dielectric losses will also be discussed and set into context of the overall aim to develop EC components for operation in EC systems.

**Keywords:** lead-free, electrocaloric effect, multilayer ceramics

**Acknowledgement:** This work was supported by the Fraunhofer Society in context of the lighthouse project "ElKaWe – Electrocaloric heat pumps".

# LEAD SCANDIUM TANTALATE THICK FILMS FABRICATED BY POWDER AEROSOL DEPOSITION

**Matteo d'Angelo[(a)], Victor Regis[(a)(b)], Ivana Goričan[(a)(b)], Silvo Drnovšek[(a)], Hana Uršič[(a)(b)]**

[(a)] Electronic Ceramics Department, Jožef Stefan Institute,
Jamova cesta 39, 1000 Ljubljana, Slovenia

[(b)]Jožef Stefan International Postgraduate School, Jamova cesta 39, 1000 Ljubljana, Slovenia

Presenting author e-mail: matteo.dangelo@ijs.si Correspondent authors: matteo.dangelo@ijs.si; hana.ursic@ijs.si;

## ABSTRACT

In recent years, electrocaloric (EC) cooling emerged as an environmentally friendly solid-state alternative to vapor-compression systems (Shi et al., 2019; Torelló and Defay, 2022). The B-site ordered $Pb(Sc_{0.5}Ta_{0.5})O_3$ (PST) ceramic is one of the most studied inorganic materials as it exhibits the highest EC temperature change in literature (Nair et al., 2019; Nouchokgwe et al., 2021). The powder aerosol deposition (PAD) method enables preparation of dense films on various substrates (e.g., polymers) enabling potential applications in microelectronics.

In this work, we prepared PST thick films on gold-coated polyimide substrates via PAD method. We prepared the B-site ordered PST pellets that were ground and milled to obtain the B-site ordered powder for deposition. The films were highly dense, with the relative density of ~99%, and the B-site order parameter of 0.89 was maintained after deposition. The functional properties of the PST films will be discussed in this contribution. Furthermore, the preparation and characterization of lead-free PAD films based on $Ba_{0.65}Sr_{0.35}TiO_3$ will also be addressed.

**Keywords:** Electrocaloric, PST, Thick film, Flexible electronics, Powder aerosol deposition

**References:**

Nair, B., Usui, T., Crossley, S., Kurdi, S., Guzmán-Verri, G.G., Moya, X., Hirose, S. and Mathur, N.D. (2019) 'Large electrocaloric effects in oxide multilayer capacitors over a wide temperature range', Nature, 575(1), pp. 468–472. doi: 10.1038/s41586-019-1634-0.

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# LANDAU APPROACH FOR PYROELECTRIC ENERGY HARVESTING IN FERROELECTRICS

**Gaspard Taxil[a,b,c,d], Gaël Sebald[d], Takahito Ono[c], Hiroki Kuwano[c], Tung Thanh Nguyen[d], Benjamin Ducharne[d], Mickaël Lallart[b]**

[a] Luxembourg Institute of Science and Technology, Esch-sur-Alzette, L-4362, Luxembourg,

gaspard.taxil@list.lu

[b] Institut National des Sciences Appliquées de Lyon, Villeurbanne, 69100, France

[c] Graduate School of Engineering, Tohoku University Sendai, 980-8579, Japan

[d] ELyTMaX IRL 3757, CNRS, Univ. Lyon, INSA Lyon, Centrale Lyon, Université Claude Bernard Lyon 1, Tohoku University, Sendai, Japan

## ABSTRACT

This study investigates the energy conversion potential of ferroelectric materials using their phase transitions for pyroelectric energy harvesting. The Olsen cycle, composed of two isothermal and two constant electric field branches, is considered as the most efficient conversion mechanism. This cycle was simulated to analyze the effects of temperature variations and crystal orientations under different electric field directions. Polarization responses were simulated using Landau–Devonshire theory. An innovative approach was then proposed to model the electrocaloric effect, validated by experimental data and first-principles calculations. The simulation successfully reproduced the negative electrocaloric effect associated with specific crystal orientation. Finally, the most promising phase transitions for pyroelectric energy harvesting were identified, achieving an energy density of about $10^2$ $mJ/cm^3$, in good agreement with previously reported results.

**Keywords:** Pyroelectric energy harvesting; Olsen cycle; Ferroelectric single crystals; Landau-Devonshire model; Electrocaloric effect

**References:**

Lheritier, P., Torelló, A. and Defay, E. (2022) 'Large harvested energy with non-linear pyroelectric modules', Nature, 609, pp. 718–721. doi: 10.1038/s41586-022-05069-2.

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**Acknowledgement:** This research was conducted within the scope of the ANR-FIESTA project, supported by the French Agence Nationale pour la Recherche, grant #ANR-20-CE05-0026, and as part of the International Research Network ELyT Global. Moreover, Gaspard Taxil acknowledges support from the European Research Council (Project 101141445 — ELEC_FROM_HEAT — ERC 2023-ADG).

# ELECTROCALORIC AND ENERGY STORAGE PROPERTIES OF MN-DOPED $(1–X)PB(FE_{0.5}NB_{0.5})O_3–XBIFEO_3$ CERAMICS

**Ivana Goričan**[a,b,*], **Tadej Rojac**[a,b], **Andreja Benčan**[a,b], **Uroš Prah**[a,c], **Hana Uršič**[a,b]

Electronic Ceramics Department, Jožef Stefan Institute, Ljubljana, 1000, Slovenia.

Jožef Stefan International Postgraduate School, Ljubljana, 1000, Slovenia.

Present address: Luxembourg Institute of Science and Technology, Esch-sur-Alzette, 4362, Luxembourg.

*Correspondence: ivana.gorican@ijs.si, +386 1 477 3498

## ABSTRACT

The $(1-x)Pb(Fe_{0.5}Nb_{0.5})O_3–xBiFeO_3$ (PFN–100*x*BFO) is an interesting ceramics system exhibiting relaxor-ferroelectric behaviour. Among the compositions, PFN–20BFO stands out as single-phase multicaloric material, exhibiting good electrocaloric and magnetocaloric properties, especially when doped with $Mn^{4+}$ and $Gd^{3+}$ ions (Prah et al., 2020a). Another notable composition is PFN–30BFO, which has potential for energy storage applications (Prah et al., 2020b). In this work, Mn-doped PFN–100*x*BFO ($x$ = 0.2, 0.3, and 0.4) ceramics were investigated. Their electrocaloric and energy storage properties were analyzed to identify the composition with the best multifunctional performance. PFN–20BFO exhibited the best electrocaloric effect, namely 0.9 °C at 65 °C and 70 kV/cm, as well as good energy storage properties, with an energy storage density of 0.7 $J/cm^3$ and an efficiency of 91% at 70 kV/cm. This makes the $x$ = 0.2 composition the most promising multifunctional material among those investigated.

**Keywords:** PFN–BFO, electrocaloric, energy storage.

**References:**

Prah, U. et al. 2020. $Pb(Fe_{0.5}Nb_{0.5})O_3–BiFeO_3$-based multicalorics with room-temperature ferroic anomalies, *J. Mater. Chem. C*, vol. 8, pp. 11282-11291. Doi: 10.1039/D0TC02329A.

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# MODELING NON-ADIABATIC EFFECTS IN ELECTROCALORIC REGENERATIVE CYCLES WITH FINITE (DE)POLARIZATION

**Darja Gačnik[a], Matija Kalin[a], Andrej Kitanovski[a]**

[a] University of Ljubljana, Faculty of Mechanical Engineering Ljubljana, 1000, Slovenija,
Andrej.Kitanovski@fs.uni-lj.si

## ABSTRACT

Electrocaloric (EC) regenerative systems transfer heat between thermal reservoirs via cyclic (de)polarization (Ožbolt et al., 2014), (Kitanovski et al., 2015). In practical devices, these transitions occur over finite durations while the EC element remains thermally coupled to the working fluid (Faye et al., 2020), resulting in thermally irreversible transitions that alter the *T-s* diagram (Plaznik et al., 2019), (Vales-Castro et al., 2023).

We present a two-dimensional transient numerical model of an ultra-high-temperature active electrocaloric regenerator (AER), based on $PbZr_{0.52}Ti_{0.48}O_3$ (PZT) thin-film multilayer (Klinar et al., 2026). The model incorporates coupled solid-fluid heat transfer, time-varying field actuation, and electric work from hysteresis loops. While the solid-state entropy trajectory is directly impacted by finite switching, its influence on COP and exergy efficiency depends on the fluid's ability to transfer heat to cold and hot reservoirs.

We evaluate the impact of (de)polarization durations across several orders of magnitude on temperature profiles, cooling and heating capacity, and exergy efficiency. The temperature evolution is examined using CFD simulations to validate the model assumptions.

**Keywords:** electrocaloric effect, active regenerative cycle, finite (de)polarization, entropy generation, numerical modeling, CFD simulations

**References:**

Faye, R. et al. (2020) 'Heat flow in electrocaloric multilayer capacitors', Journal of Alloys and Compounds, 834, article 155042. doi: 10.1016/j.jallcom.2020.155042.

Kitanovski, A. et al. (2015) 'Present and future caloric refrigeration and heat-pump technologies', International Journal of Refrigeration, 57, pp. 288–298. doi: 10.1016/j.ijrefrig.2015.06.008.

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Vales-Castro, P. et al. (2023) 'Direct visualization of antiferroelectric switching dynamics via electrocaloric imaging', Advanced Electronic Materials, 9(15), article 2300720. doi: 10.1002/aelm.202300720.

**Acknowledgement:** The authors acknowledge the financial support of the Slovenian Research Agency for the research core funding no. P2-0223 Heat and Mass Transfer.

*ORAL PRESENTATIONS*

## S05 Thermoelectrics and magneto-thermoelectrics

LINHART HALL

Chair **Llibertat Abad Muñoz** · Co-chair **Shoya Ohsumi** · Help **Adam Plantarič**

17:30 Height-optimised micro thermoelectric devices for hot-spot cooling and low-gradient energy harvesting
**Heiko Reith** · *IFW Dresden*

17:42 Te-free thermoelectric modules with ALD surface protection for sustainable power and cooling
**Ran He** · *IFW Dresden*

17:54 Full-scale thermoelectric heat pump booster for low-temperature district heating substation
**Urban Tomc** · *FME, University of Ljubljana*

18:06 Behaviour of magnesium-based and tellurium-free thermoelectric modules under real operating conditions
**Esteban Zuñiga Puelles** · *IFW Dresden*

# HEIGHT-OPTIMIZED MICRO THERMOELECTRIC DEVICES FOR HOT-SPOT COOLING AND LOW-GRADIENT ENERGY HARVESTING

**Heiko Reith[(a)], Nithin B Pulumati[(a,b)], Adhiraj Sundar[(a,b)], Kornelius Nielsch[(a,b)]**

[(a)]Institute for Metallic Materials, Leibniz Institute of Solid State and Materials Research, Dresden, 01069, Germany, h.reith@ifw-dresden.de

[(b)]TU Dresden, Faculty of Mechanical Engineering, Dresden, 01069, Germany

## ABSTRACT

Electrochemical deposition enables efficient fabrication of micro thermoelectric devices (µTEDs) compatible with on-chip integration for hotspot cooling and self-powered sensing (Zhang et al., 2022). This work presents a new design strategy that optimizes device height rather than cross-sectional area, increasing packing density, cooling power, and output power while reducing the use of toxic and costly thermoelectric materials. µTEDs were fabricated using photolithography and electrochemical deposition of $Bi_2(Te_xSe_{1-x})_3$ (n-type) and Te (p-type) (Dutt et al., 2022, 2025, Li et al 2018). Nitrogen injection into the electrolyte minimized oxygen incorporation, lowering contact resistance and enhancing performance. The area- and height-optimized µTEDs achieved maximum cooling of 10.8 K and 10.5 K at room temperature, respectively, and 21 K at 343 K for height-optimized devices, with 75% less Te consumption. Finite element simulations confirmed cooling densities of hundreds of W $cm^{-2}$. As generators, µTEDs produced milliwatt-level power densities at small temperature differences. These results demonstrate efficient, scalable µTEDs for on-chip cooling and energy-autonomous IoT and biomedical applications.

**Keywords:** Thermoelectric devices, micro thermoelectric devices, micro thermoelectric coolers, geometry optimization, electrochemical deposition, contact resistance

**References:**

Dutt, et al., Advanced Electronic Materials 8, 2101042 (2022), DOI: 10.1002/aelm.202101042

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Zhang et al., Nature Electronics 5, 333-347 (2022), DOI: 10.1038/s41928-022-00776-0

**Acknowledgement:** The author acknowledges funding from the (Bundesministerium für Forschung, Technologie und Raumfahrt) within grant number 16ME1032.

# TE-FREE THERMOELECTRIC MODULES WITH ALD SURFACE PROTECTION FOR SUSTAINABLE POWER AND COOLING

**Pingjun Ying, Ran He, Heiko Reith, Kornelius Nielsch**

Institute for Metallic Materials, Leibniz Institute for Solid State and Materials Research, Helmholtzstraße 20, 01069 Dresden, Germany.

p.ying@ifw-dresden.de; r.he@ifw-dresden.de; h.reith@ifw-dresden.de; k.nielsch@ifw-dresden.de

## ABSTRACT

Commercial Thermoelectric (TE) modules are based on $Bi_2Te_3$ compounds because of their unrivalled TE properties at low-grade heat-related temperatures (<550 K). However, the scarcity of elemental Te severely limits the applicability of these modules. Here, we present the performance of TE modules assembled from Te-free compounds, including p-type MgAgSb and n-type $Mg_3(Sb,Bi)_2$, using a simple, versatile, and scalable processing routine. To further improve stability, atomic layer deposition (ALD) coatings were applied to protect the surfaces of Mg-based legs, which significantly extended the operational lifetime of the modules. We demonstrate module-level conversion efficiencies of 3% and 8.5% for temperature differences of 75 K and 260 K, respectively, as well as maximum cooling of 72 K when used as a cooler. These proofs of principle pave the way for robust, high-performance, and sustainable solid-state power generation and cooling to replace the highly rare and toxic $Bi_2Te_3$.

**Keywords:** Thermoelectric modules; Tellurium-free materials; Magnesium-based compounds; Atomic layer deposition (ALD); Energy conversion; Device stability

**References:**

Ying, P., He, R., Mao, J., Zhang, Q., Reith, H., Sui, J., Ren, Z., Nielsch, K. and Schierning, G. (2021) 'Towards tellurium-free thermoelectric modules for power generation from low-grade heat', *Nature Communications*, 12, article 1121. doi: 10.1038/s41467-021-21391-1.

Ying, P., Reith, H., Nielsch, K. and He, R. (2022a) 'Geometrical Optimization and Thermal Stability Characterization of Te Free Thermoelectric Modules Based on MgAgSb/Mg3(Sb,Bi)2', *Small*, 18, article 2201183. doi: 10.1002/smll.202201183.

Ying, P., Wilkens, L., Reith, H., Rodriguez, N.P., Hong, X., Lu, Q., Hess, C., Nielsch, K. and He, R. (2022b) 'A robust thermoelectric module based on MgAgSb/Mg3(Sb,Bi)2 with a conversion efficiency of 8.5% and a maximum cooling of 72 K', *Energy & Environmental Science*, 15, pp. 2557–2566. doi: 10.1039/D2EE00883A.

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**Acknowledgement:** The State of Saxony via the M-ERA NET THERMOS project and European Union's Horizon Europe research and innovation programme (ERC Starting Grant, TENTATION, 101116340).

# FULL-SCALE THERMOELECTRIC HEAT PUMP BOOSTER FOR LOW TEMPERATURE DISTRICT HEATING SUBSTATION

**Urban Tomc[(a)], Simon Bogić[(a)], Boris Vidrih[(a)], Jakob Perne[(a)], Miha Bobič[(b)], Andrej Kitanovski[(a)]**

[(a)] University of Ljubljana, Faculty of Mechanical Engineering, Laboratory for Refrigeration and District Energy, Ljubljana, Slovenia, andrej.kitanovski@fs.uni-lj.si

[(b)] Danfoss Trata d.o.o., Ljubljana, Slovenia, miha.bobic@danfoss.com

## ABSTRACT

One key energy efficiency measure in district heating (DH) systems is lowering supply and return temperatures. Fourth-generation DH operates at 50–60 °C, enabling better use of renewable and waste heat sources. Fifth-generation systems operate at even lower temperatures, requiring additional heat sources—boosters—for domestic hot water. These boosters may include vapor compression heat pumps, gas or electric boilers, waste heat, or solar energy.

We present an alternative: a full-scale thermoelectric heat pump that can serve as a booster in a DH substation. A parametric experimental analysis revealed the system's capability to deliver up to 5.5 kW heating power and increase the DH supply temperature by up to 45 K, all while maintaining a compact, silent, and vibration-free operation. Operating in the 1–2 kW range, the system raises supply temperatures by 10–20 K, achieving a $COP_H$ of 2.4–1.6, significantly outperforming direct fuel or electricity-to-heat conversion, where $COP_H$ is typically below 1.

**Keywords:** thermoelectric, Peltier, booster, heat pump, district heating

**Acknowledgement:** We would like to acknowledge the support from Project Greentech: Hybrid technologies for green factories of the future.

# BEHAVIOR OF MAGNESIUM-BASED AND TELLURIUM-FREE THERMOELECTRIC MODULES UNDER REAL OPERATING CONDITIONS

**Esteban Zuñiga-Puelles[(a)], Yongchen Rao[(a)], Pingjun Ying[(a)] Kornelius Nielsch[(a,b,c)]**

[(a)] Leibniz Institute for Solid State and Materials Research (IFW) Dresden e.V. Dresden 01069, Saxony, Germany, e.zuniga.puelles@ifw-dresden.de

[(b)] Institute of Materials Science, TUD Dresden University of Technology Dresden 01069, Saxony, Germany

[(c)] Institute of Applied Physics, TUD Dresden University of Technology Dresden 01069, Saxony, Germany

## ABSTRACT

Thermoelectric modules are solid-state devices that enable the direct conversion of heat into electrical energy and vice versa, which have found multiple routes toward technological implementation. However, most commercial modules still rely on materials that are either toxic or expensive, such as tellurium compounds. Recent advances in magnesium-based and tellurium-free materials have shown significant improvements, offering competitive and sustainable alternatives for practical applications. In this work, we explore the behavior of this new generation of modules under realistic operating conditions for: i) energy harvesting to power autonomous devices and ii) localized cooling for thermal control. The results shed light on their performance and stability under application scenarios, providing valuable insights for potential uses in future energy-efficient systems. This work contributes to the broader understanding of environmentally friendly thermoelectric technologies and supports the transition from laboratory research toward practical devices.

**Keywords:** Thermoelectric modules, Energy Harvesting, Peltier Cooling, Tellurium-free materials, Sustainable Technologies

**References:**

He, S. et al. (2021) ‘Current State-of-the-Art in the Interface/Surface Modification of Thermoelectric Materials’, Advanced Energy Materials, 11(37), article 2101877. doi: 10.1002/aenm.202101877.

Ying, P. et al. (2021) ‘Towards tellurium-free thermoelectric modules for power generation from low-grade heat’, Nature Communications, 12(1), article 1121. doi: 10.1038/s41467-021-21391-1.

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Ying, P. et al. (2022b) ‘A robust thermoelectric module based on MgAgSb/Mg3(Sb,Bi)2 with a conversion efficiency of 8.5% and a maximum cooling of 72 K’, Energy & Environmental Science, 15, pp. 2557–2566. doi: 10.1039/d2ee00883a.

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## S06 Multicalorics and multipyro KOSOVEL HALL

Chair **Daniel Salazar** · Co-chair **Claudia Masselli** · Help **Nene Narh Teinor**

**17:30** Numerical design and performance assessment of MULTICAL: a hybrid multicaloric heat pump
**Sabrina Gargiulo** · *University of Naples Federico II*

**17:42** Room-temperature multicaloric composite thick films prepared by the powder aerosol deposition method
**Victor Regis** · *Jožef Stefan Institute*

**17:54** Enhancing mechanical stability of Heusler alloys via the powder-in-tube method
**Timo Niehoff** · *Helmholtz-Zentrum Dresden-Rossendorf*

**18:06** Comparative study of melt-spun and suction-cast $Ni_{36}Co_{14}Mn_{37}Ti_{13}$ Heusler alloys for multicaloric cooling
**Ali Ghotbi Varzaneh** · *Karlsruhe Institute of Technology*

**18:18** Additive manufacturing of Heusler alloys: tailoring microstructure and caloric properties via laser powder bed fusion
**Nene Narh Teinor** · *TU Darmstadt — Functional Materials*

# NUMERICAL DESIGN AND PERFORMANCE ASSESSMENT OF MULTICAL: A HYBRID MULTICALORIC HEAT PUMP

**Luca Cirillo[(a)], Sabrina Gargiulo[(a)], Adriana Greco[(a)], Claudia Masselli[(a),*] Vincenzo Orabona[(a)], Lucrezia Verneau[(a)]**

(a) Department of Industrial Engineering, University of Naples Federico II P.le Tecchio 80, 80125 Naples Italy

* corresponding author e-mail: claudia.masselli@unina.it ; +390817682380

## ABSTRACT

The growing need for sustainable and efficient thermal management has renewed interest in solid-state heat pumps based on caloric effects (Takeuchi, Sandeman, 2015). These systems exploit reversible temperature changes induced by magnetic, electric, or mechanical fields, enabling the use of solid materials as zero-GWP refrigerants (Fähler et al., 2018). However, single-field caloric devices still face limitations due to high field requirements and restricted temperature spans. The MULTICAL project introduces a novel approach by exploiting the multicaloric effect, where two or more caloric responses are simultaneously or sequentially activated within the same material or device. Depending on the material properties, different dual-field couplings (e.g., magneto–elasto-, electro–baro-, magneto–electrocaloric) can be tailored to improve efficiency and durability. A numerical investigation was carried out to model and optimize the MULTICAL heat pump. The magneto-baro $MnCoGe_{0.99}In_{0.01}$ and elasto-electro $(Ba_{0.5}Sr_{0.5})TiO_3$ are the materials under test. The multicaloric behaviour of MULTICAL heat pump working with $(Ba_{0.5}Sr_{0.5})TiO_3$ always overestimates (+ 30% on temperature span, +62% on cooling power) the multicaloric behaviour of the system employing $MnCoGe_{0.99}In_{0.01}$. The simulations highlight how hybrid caloric activation enhances temperature span and COP, paving the way for next-generation, fully eco-friendly refrigeration systems.

**Keywords:** Multicaloric effect; Solid-state heat pump; Caloric materials; Finite element method; Energy efficiency

**References:**

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**Acknowledgement:** The study is realized whitin the project MULTICAL that is financially supported by the 2022 internal grant reserved for Fixed-Term Research of University of Naples Federico II within the program FRA 2022 (Finanziamento Ricerca di Ateneo 2022) - University Research Funding 2022 University of Naples Federico II, Italy.

# ROOM-TEMPERATURE MULTICALORIC COMPOSITE THICK FILMS PREPARED BY THE POWDER AEROSOL DEPOSITION METHOD

**Victor Regis[a,b*], Matej Šadl[a], Andreja Benčan[a,b], Goran Dražić[a,b,c], Sašo Gyergyek[a], Ivana Gorican[a,b], Urban Tomc[d], Enric Stern-Taulats[e], Klara Lünser[e], Lluís Mañosa[e] and Hana Uršič[a,b]**

[a] Jožef Stefan Institute, 1000 Ljubljana, Slovenia

[b] Jožef Stefan International Postgraduate School, 1000 Ljubljana, Slovenia

[c] Department of Materials Chemistry, National Institute of Chemistry, 1000 Ljubljana, Slovenia

[d] Faculty of Mechanical Engineering, University of Ljubljana, 1000 Ljubljana, Slovenia

[e] Departament de Física de la Matèria Condensada, Facultat de Física, Universitat de Barcelona, 08028 Barcelona,Catalonia

*Correspondence: victor.regis@ijs.si

## ABSTRACT

In pursuit of better cooling technologies, research has been made on combining different caloric effects, namely the multicaloric effect (Hou et al., 2022; Stern-Taulats et al., 2018). However, the combination of electrocaloric (EC) and magnetocaloric (MC) in composite materials remains mostly unexplored. In light of this, using the powder aerosol deposition method, we prepared composite thick films that combine both EC and MC phases. Our results show that the composites exhibit an EC temperature change as high as 0.44 K at 250 kV $cm^{-1}$ and room temperature, a significant enhancement compared to the 0.3 K in the EC-only samples. In addition, the composites exhibit a room temperature MC output of ~1.4 K at 2 T. For the first time, thick-film composites joining together EC and MC effects have been successfully prepared and directly characterized at room temperature, thereby expanding the possibilities of caloric applications.

**Keywords:** powder aerosol deposition; electrocaloric; magnetocaloric; multicaloric; thick films

**References:**

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# ENHANCING MECHANICAL STABILITY OF HEUSLER ALLOYS VIA THE POWDER METHOD

**Timo Niehoff[a, b], Lukas Beyer[c, d], Johannes Puy[e], Jens Freudenberger[c, d], Oliver Gutfleisch[e], Jochen Wosnitza[a, b], Franziska Scheibel[e], Tino Gottschall[a]**

[a] Dresden High Magnetic Field Laboratory (HLD-EMFL), Dresden, 01328, Germany, t.niehoff@hzdr.de

[b] Institut für Festkörper- und Materialphysik, TU Dresden, Dresden, 01069, Germany

[c] Leibniz-Institut für Festkörper- und Werkstoffforschung IFW, Dresden, 01069, Germany

[d] TU Bergakademie Freiberg, Freiberg, 09599, Germany

[e] Institute of Materials Science, Technical University of Darmstadt Darmstadt, 64287, Germany

## ABSTRACT

We address the long-standing problem of mechanical fatigue in Heusler-based elastocaloric and multicaloric materials by applying the Powder-in-Tube (PIT) method. This approach significantly enhances the mechanical robustness of Heusler materials. Using cyclic loading up to 100,000 cycles and high-load tests, we demonstrate that PIT samples maintain their structural integrity, with only minor, non-critical cracks at the sample ends while the core remains fully thermally connected to the steel shell. Even after plastic deformation, the Heusler core stays intact. Magnetization measurements before and after cycling show only minimal changes, confirming the material's durability. Furthermore, magnetocaloric measurements reveal excellent thermal coupling between the Heusler core and the metallic shell. Our results show that the PIT method increases the operational lifetime of Heusler alloys by several orders of magnitude compared to bulk samples, enabling independent optimization of mechanical stability and caloric performance.

**Keywords:** Magnetocaloric, Elastocaloric, Multicaloric, Heusler alloys

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# COMPARATIVE STUDY OF MELT-SPUN AND SUCTION-CAST $NI_{36}CO_{14}MN_{37}TI_{13}$ HEUSLER ALLOYS FOR MULTICALORIC COOLING

**Ali Ghotbi Varzaneh**[(a)*], **Mariana Ríos**[(b)], **Gowtham Arivanandhan**[(a)], **Amir-Abbas Haghighirad**[(c)], **Manfred Kohl**[(a)], **Daniel Salazar**[(b)], **Jingyuan Xu**[(a)*]

[(a)] Institute of Microstructure Technology, Karlsruhe Institute of Technology, Karlsruhe, 76344, Germany

[(b)] BCMaterials, Basque Center for Materials, Applications and Nanostructures, UPV/EHU Science Park, Leioa, 48940, Spain

[(c)] Institute for Quantum Materials and Technologies, Karlsruhe Institute of Technology, Karlsruhe, 76021, Germany

* Corresponding authors: Ali Ghotbi Varzaneh, Tel.: +49 721 608-22747, E-mail: ali.ghotbi@kit.edu ; and Jingyuan Xu, Tel.: +49 721 608-24781, E-mail: jingyuan.xu@kit.edu

## ABSTRACT

All-d-metal Heusler alloys have attracted increasing attention as promising candidates for multicaloric materials, owing to their ability to exhibit multiple caloric effects under different external stimuli. In this study, the $Ni_{36}Co_{14}Mn_{37}Ti_{13}$ alloy was synthesized by arc melting and subsequently processed into two forms: melt-spun ribbons and suction-cast tubular samples. Structural and magnetic characterizations showed that the sample stabilize in a B2 phase and undergo a martensitic transformation between 275-300 K (ribbons) and 380-425 K (suction-cast). The melt-spun ribbons, transforming near room temperature, were ideal for magnetocaloric studies. Microscopic observations revealed grain-dependent behavior, with the wheel-side showing ridges and valleys from rapid solidification, while the free-side contained fine cavities that may limit mechanical reliability for elastocaloric response. Conversely, the suction-cast tubes, after an optimized heat treatment to induce the martensitic transformation demonstrated excellent mechanical strength. These results highlight suction-cast $Ni_{36}Co_{14}Mn_{37}Ti_{13}$ as a candidate for realizing combined magneto- and elastocaloric functionality in all-d-metal Heusler systems.

**Keywords:** All-d-metal Heusler-type alloys, Martensitic Transformation, Mechanical properties, Magnetocaloric effect

**Acknowledgement:** Ali Ghotbi Varzaneh acknowledges funding from the Alexander von Humboldt Foundation.

# ADDITIVE MANUFACTURING OF HEUSLER ALLOYS: TAILORING MICROSTRUCTURE AND CALORIC PROPERTIES VIA LASER POWDER BED FUSION

**Nene Narh Teinor[(a)], Johannes Puy[(a)], Adrian Guder[(b)], Christian Lauhoff[(b)], Thomas Niendorf[(b)], Oliver Gutfleisch[(a)], Franziska Scheibel[(a)]**

[(a)] Functional Materials, Institute of Materials Science, Technical University of Darmstadt Darmstadt, 64287, Germany, nene.teinor@tu-darmstadt.de

[(b)] Metallic Materials, Institute of Materials Engineering, University of Kassel, Kassel, 34125, Germany

## ABSTRACT

Heusler alloys like Ni–Mn–Sn and Ni–Co–Mn–Ti show strong potential for solid-state cooling due to their first-order magnetostructural transitions (FOMST) (Beckmann et al., 2025, Scheibel et al., 2018). However, their functional performance is highly sensitive to processing conditions [3]. In this work, bulk samples are produced via Laser Powder Bed Fusion (PBF-LB/M) using gas-atomized powders to explore the influence of additive manufacturing parameters on microstructure and caloric properties. By varying laser power, scan speed, and strategy, we achieve controlled tuning of martensitic, austenitic, and Curie temperatures, as well as reduced thermal hysteresis. Structural, compositional, and magnetic analyses reveal how rapid solidification enhances the sharpness and reversibility of FOMST. We demonstrate that additive manufacturing not only preserves the functional properties of these alloys but also enables active enhancement of their tunability of transition behavior compared to conventionally processed samples.

**Keywords:** Multicalorics, Heusler Alloys, Laser Powder Bed Fusion, Transition Temperature Tuning.

**References:**

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## S07 Thermal Control Devices — LINHART HALL

Chair **Miguel Muñoz Rojo** · Co-chair **Karl Joulain** · Help **Blaž Velkavrh**

11:30 Bridging the thermal gap: the role of fluidic and mechanical thermal control devices in advancing caloric technologies
**Katja Klinar** · *FME, University of Ljubljana*

11:42 Role of adhesion and air ionisation in film-based electrostatic actuation
**Elie Zoghbi** · *Université Paris-Saclay, ENS Paris-Saclay*

11:54 A $VO_2$ film-based thermochromic optical modulator
**Danni Li** · *Karlsruhe Institute of Technology*

12:06 Digital microfluidic thermal switch capacitors for magnetocaloric cooling
**Blaž Velkavrh** · *FME, University of Ljubljana*

12:18 Thermal conductivity of cellulose-based composite films
**Vanja Kokol** · *FME, University of Maribor*

12:30 Phase-change material thermal diodes for caloric refrigerator
**Karl Joulain** · *Université de Poitiers*

12:42 Enhancing solid-state thermal rectification via temperature-dependent thermal contact resistance
**Katja Vozel** · *FME, University of Ljubljana*

12:54 Theoretical analysis of heat spreading in hexagonal boron nitride structures for thermal diode fabrication
**Timm Swoboda** · *ICN2 — Catalan Inst. of Nanoscience & Nanotechnology*

13:06 Passive magnetically-actuated thermal regulator: stationary and oscillating regimes
**Katie Barcak** · *Rice University*

# BRIDGING THE THERMAL GAP: THE ROLE OF FLUIDIC AND MECHANICAL THERMAL CONTROL DEVICES IN ADVANCING CALORIC TECHNOLOGIES

**Katja Klinar[(a)], Urban Tomc[(a)], Katja Vozel[(a)], Andrej Kitanovski[(a)]**

[(a)] Faculty of Mechanical Engineering, University of Ljubljana Ljubljana, 1000, Slovenia, katja.klinar@fs.uni-lj.si

## ABSTRACT

The development of caloric technologies faces a key bottleneck in efficient thermal control. Conventional heat transfer – convection used in active regenerators does not enable operation at frequencies above 5 Hz. To address these limitations, advanced fluidic and mechanical thermal control devices are emerging as essential components for improving performance, stability, and efficiency. These devices - such as thermal switches, diodes, and variable-conductance conduits- enable active, nonlinear, and reversible management of heat flow, analogous to electronic control in electrical circuits. This work reviews the current state of research on fluidic and mechanical thermal control devices specifically applied to caloric refrigeration and heat pumping systems. Emphasis is placed on their operational principles, integration challenges, and potential to enhance heat exchange, reduce response time, and increase overall energy efficiency. Finally, key design guidelines and research targets are outlined for enabling the next generation of high-performance caloric devices.

**Keywords:** thermal switch, thermal diode, thermal regulator, magnetocaloric, electrocaloric, mechanocaloric, heat transfer, refrigeration, heat pump, high temperature, solid-state

**References:**

K. Klinar, A. Kitanovski, Thermal control elements for caloric energy conversion, Renewable and Sustainable Energy Reviews, Volume 118, 2020, 109571, https://doi.org/10.1016/j.rser.2019.109571

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# ROLE OF ADHESION AND AIR IONIZATION IN FILM-BASED ELECTROSTATIC ACTUATION

**Elie Zoghbi[(a)], Emilien Dufresne[(a)], Martino LoBue[(a)], Morgan Almanza[(a)]**

[(a)] Université Paris-Saclay, École Normale Supérieure Paris-Saclay, CNRS, Laboratoire SATIE Gif-sur-Yvette, 91190, France, elie.zoghbi@ens-paris-saclay.fr

## ABSTRACT

Electrostatic actuation (EA) on electrocaloric (EC) films plays an important role in transferring heat in cooling devices (Ma *et al.*, 2017) and thermal switches (Almanza *et al.*, 2018), where heat is exchanged by the moving active film. Understanding actuation losses is crucial for improving efficiency, but it is difficult due to the interplay between adhesion and partial discharges. Analyzing the position of the film via the capacitance versus the voltage reveals that a minimum voltage of around 90 V is required to begin the EA motion. On the other hand, the actuation efficiency and forces can be reduced by the appearance of charges on the film surface when the voltage exceeds 450 V. Their presence is proven by fitting the electrostatic force and current measurements. Here, we study the EA working voltage range, between the lower bound related to adhesion forces and the upper bound due to air ionization (Husain and Nema, 1982), and there is a lower limit of 1.44 $\mu J/cm^2$ for the actuation losses, a detrimental effect for thermal switches.

**Keywords:** Cooling device, thermal switches, films, electrocaloric (EC) effect, electrostatic actuation (EA)

**References:**

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**Acknowledgement:** This work has been supported by France's national research agency on the ANR-20-CE05-0044 and ANR-23-CE05-0012

# A $VO_2$ FILM-BASED THERMOCHROMIC OPTICAL MODULATOR

**Danni Li[(a)], Jill Fortmann[(b)], Alfred Ludwig[(b)], Manfred Kohl[(a)]**

[(a)] Institute of Microstructure Technology, Karlsruhe Institute of Technology (KIT)

Karlsruhe, 76021, Germany, manfred.kohl@kit.edu

[(b)] Institute for Materials, Ruhr University Bochum (RUB), Bochum, 44801, Germany

## ABSTRACT

The phase change material Vanadium dioxide ($VO_2$) undergoes a reversible phase transformation from an insulating monoclinic to a metallic tetragonal phase at approximately 68 °C. The resulting pronounced thermochromic effect is of special interest for photonic switching (Cueff et al., 2020). Here, we present the development of an optical modulator using the large transmission contrast of a magnetron-sputtered $VO_2$ film on a silicon waveguide. Gold microheaters are integrated to induce the phase transformation in the $VO_2$ film through local Joule heating. The relationship between the input electrical power and maximum heater temperature as well as the concept of optical modulation is explored experimentally and by finite element simulations for $VO_2$ films with various lengths and thicknesses. First demonstrators show an optical modulation depth up to 9 dB. Our results indicate that the proposed modulator enables a reduced footprint and lower required electrical power compared to previously reported metal heater integrated VO2-based modulators (Jeyaselvan et al., 2019), (Sánchez et al., 2018).

**Keywords:** phase change material, vanadium dioxide, metal-to-insulator transition, thermochromic effect, thermally induced optical modulation

**References:**

Cueff, S. et al. (2020) 'VO2 nanophotonics', APL Photonics, 5(11). doi: 10.1063/5.0028093

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**Acknowledgement:** This research was funded by the German Science Foundation (DFG). This work was partly carried out with the support of the Karlsruhe Nano Micro Facility (KNMFi, www.knmf.kit.edu), a Helmholtz Research Infrastructure at Karlsruhe Institute of Technology (KIT, www.kit.edu).

# DIGITAL MICROFLUIDIC THERMAL SWITCH CAPACITORS FOR MAGNETOCALORIC COOLING

**Blaž Velkavrh[(a), (b), (c)], Hana Uršič[(b), (c)], Urška Erjavec Nagode[(a)], Andrej Kitanovski[(a)], Lukas Beyer[(d), (e)], Jens Freudenberger[(d), (e)], Klara Lünser[(f)], Enric Stern-Taulats[(f)], Lluis Mañosa[(f)] and Urban Tomc[(a),*]**

[(a)]University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva cesta 6, 1000 Ljubljana, Slovenia

[(b)]Jožef Stefan Institute, Electronic Ceramic Department, Jamova cesta 39, 1000 Ljubljana, Slovenia

[(c)]Jožef Stefan International Postgraduate School, Jamova cesta 39, 1000 Ljubljana, Slovenia

[(d)]Leibniz Institute for Solid State and Materials Research Dresden, Helmholtzstr. 20, 01069 Dresden, Germany

[(e)]TU Bergakademie Freiberg, Gustav-Zeuner-Str. 5, 09599 Freiberg, Germany

[(f)]University of Barcelona, Department of Condensed Matter Physics, Martí i Franquès, 1-11, 08028 Barcelona, Spain

*Corresponding author, phone number: +386 1 4771 513, email: urban.tomc@fs.uni-lj.si

## ABSTRACT

Vapour-compression has become a well-developed technology for refrigeration and air conditioning. However, it suffers from environmental problems of refrigerants and moderate efficiency. An alternative is magnetocaloric energy conversion. Despite showing great potential, today's magnetocaloric devices have issues with inefficiency in heat transfer. In light of this, we are preparing unique fluidic thermal switch capacitors for magnetocaloric cooling applications that are based on electrowetting-on-dielectric (EWOD).

In this work, we prepared multilayer structures, consisting of electrode and SU-8 dielectric layers and investigated the EWOD effect of distilled water droplet. Initial contact angle $\theta$ is 113°, while the contact angle decreases to 90° at 100 V and to 83° at 175 V. The decrease in the contact angle of the water droplet was further used in numerical analysis to test the principle of thermal switch capacitor operation, as well as to numerically confirm the successful cooling with a magnetocaloric device.

**Keywords:** digital microfluidics, electrowetting, thermal switch capacitor, magnetocaloric cooling

**Acknowledgement:** The authors acknowledge financial support from the transnational consortium M-ERA.NET for the project Cool BatMan: Battery Thermal Management System Based on High Power Density Digital Microfluidic Magnetocaloric Cooling (No. 9400). This project is co-financed with tax funds on the basis of the budget adopted by the Saxon state parliament. SAB-Nr: 100632843.

# THERMAL CONDUCTIVITY OF CELLULOSE-BASED COMPOSITE FILMS

**Vanja Kokol[(a)], Vera Vivod[(a)], Katja Klinar[(b)]**

[(a)]University of Maribor, Faculty of Mechanical Engineering, Slovenia, vanja.kokol@um.si

[(b)]University of Ljubljana, Faculty of Mechanical Engineering, Slovenia; katja.klinar@fs.uni-lj.si

## ABSTRACT

The use of biopolymers in advanced (opto)electronics and wearable sensor devices has attained extensive attention recently, above all, to replace non-biodegradable dielectric thermoplastic polymers (as PI, PVDF) while maintaining the device's flexibility and increasing their recyclability. The nanocellulose/NC has gained particular attention due to its biocompatibility, cost-effectiveness, and film-forming properties. However, all of these materials are thermal insulators, while attached electronic components produce heat by Joule (resistive) effect during operation, which negatively affects their performance and also softens thermoplastics. The thermal diffusivity of NC films can be obtained by reducing the thermal resistance at the interface between the cellulose nanofibrils/crystals with an increased interaction through their highly aligned anisotropic structure and/or introduced thermally-conductive 2D nanofillers. In this contribution, we will present the influence of NC type and addition of hexagonal boron nitride (hBN) of various lateral sizes on structural and thermal conductivity properties of such films.

**Keywords:** Nanocellulose, hBN, films, thermal conductivity.

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# PHASE-CHANGE MATERIAL THERMAL DIODES FOR CALORIC REFRIGERATOR

**Karl Joulain[b], Katja Klinar[a], Katja Vozel[a], Andrej Kitanovski[a], Younès Ezzahri[b]**

[a] Faculty of Mechanical Engineering, University of Ljubljana, Askerceva 6, 1000 Ljubljana, Slovenia

[b] Institut Pprime, CNRS, Université de Poitiers, ISAE-ENSMA, F-86962 Futuroscope Chasseneuil, France.

karl.joulain@univ-poitiers.fr

## ABSTRACT

Phase change materials such as Vanadium Dioxide, polyethylen or nitinol have been studied recently to conceive and build thermal elements such as thermal diode (Ito et al., 2014),(Haratoka et al., 2023), thermal transistor (Ben-Abdallah et al., 2014) or thermal memristor (Ordonez-Miranda et al., 2019). Moreover, solid-state refrigerators have been conceived using magnetocaloric or electrocaloric materials (Klinar et al., 2020a) whose performances strongly depend on the functioning of thermal switches (Klinar et al., 2020b), in particular their operating frequency and their switching ratio (Klinar et al., 2022). Another issue is the reliability of thermal switches that often comprise moving pieces. In this context, phase change materials appear as a way to conceive a full solid-state caloric refrigerator without any moving piece.In this work, we explore and determine the properties (conductivity contrast, latent heat, critical temperature) that a phase change material entering in the composition of such a refrigerator should have in order to obtain a cooling device exhibiting cooling power and coefficient of performance comparable to conventional technologies.

**Keywords:** Thermal control elements, caloric refrigerator, phase change materials, thermal switch, heat transfer

**References:**

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# ENHANCING SOLID-STATE THERMAL RECTIFICATION VIA TEMPERATURE-DEPENDENT THERMAL CONTACT RESISTANCE

**Katja Vozel[(a)], Andrej Kitanovski[(a)]**

[(a)] Faculty of Mechanical Engineering, University of Ljubljana Ljubljana, 1000, Slovenia,
Andrej.Kitanovski@fs.uni-lj.si

## ABSTRACT

Macroscopic solid-state thermal diodes (MSTDs) are compact and scalable devices that offer fully passive directional heat control. However, their rectification factors (RF) remain too low for practical use. This work investigates improving MSTD performance by exploiting the temperature dependence of thermal contact resistance (TCR) between constituting materials at low temperatures. As TCR increases exponentially with decreasing temperature, due to the transition from diffusive to ballistic heat transport (Dhuley et al., 2019), it can enhance asymmetric heat flow across interfaces. Numerical simulations based on Fourier's law and the finite volume method include temperature-dependent thermal conductivities and TCRs for selected material pairs (Stoner et al., 1993), (Swartz et al., 1987). Results show that temperature-dependent TCR can raise RF from 0.006 to 0.94 near absolute zero at a 5 K bias. Moderate improvement also occurs at slightly higher temperatures, where TCR still varies with temperature. These results show that leveraging TCR temperature dependence can greatly enhance MSTD efficiency in cryogenic systems such as spacecraft, electronics, and sensors.

**Keywords:** Heat transfer, Thermal diode, Thermal rectification, Thermal management, Cryogenics

**References:**

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**Acknowledgement:** The authors acknowledge the financial support of the Slovenian Research Agency for the project TCCbuilder: An open-source simulation tool for thermal control circuits J7-3148 and the project Development of anisotropic thermally conducting and insulating substrates for recyclable flexible electronics J2-60048, and the research core funding no. P2-0223 Heat and Mass Transfer. The authors thank all members of the lab for their support.

# THEORETICAL ANALYSIS OF HEAT SPREADING IN HEXAGONAL BORON NITRIDE STRUCTURES FOR THERMAL DIODE FABRICATION

**Timm Swoboda[(a)], Markos Poulos[(b)], Joseph Kioseoglou[(c,d)], Konstantinos Termentzidis[(b)], Marianna Sledzinska[(a)]**

[(a)]Catalan Institute of Nanoscience and Nanotechnology (ICN2), CSIC and BIST, Barcelona, 08193, Spain, timm.swoboda@icn2.cat

[(b)]INSA Lyon, CNRS, CETHIL, UMR5008, Villeurbanne, 69621, France, markos.poulos@insa-lyon.fr

[(c)]Department of Physics, Faculty of Sciences, Aristotle University of Thessaloniki, 54124, Thessaloniki, Greece

[(d)]Center for Interdisciplinary Research & Innovation (CIRI), Aristotle University of Thessaloniki, 57001 Thessaloniki, Greece, sifisl@auth.gr

## ABSTRACT

Understanding heat spreading in nanoscale devices remains essential for the design of future electronics. One limiting factor in this context is thermal crosstalk between adjacent components (Pande et al., 2024). In this work, we present a theoretical study of heat spreading in hexagonal boron nitride (hBN) monolayers. A simplified linear three-device finite element method model was developed to evaluate the thermal crosstalk between them. The central component is thermally coupled to two outer ones through a hBN monolayer exhibiting asymmetric thermal conductivity $k$ defined by a rectification ratio ($RR = k_{high}/k_{low}$). We observed a continuous reduction of the thermal coupling between the devices as a function of $RR$, decreasing from 70% to 55% for values of $RR$ up to 5. Building on these results, we developed thermal diode designs based on asymmetric shaped hBN using molecular dynamics to optimize such structures, followed by the fabrication and experimental characterization of their thermal rectification characteristics.

**References:**

Pande, S., Chakrabarti, B., Chakravorty, A., 2024. Thermal Crosstalk Analysis in RRAM Passive Crossbar Arrays, in: 2024 37th International Conference on VLSI Design and 2024 23rd International Conference on Embedded Systems (VLSID). IEEE, Kolkata, India.

# PASSIVE MAGNETICALLY-ACTUATED THERMAL REGULATOR: STATIONARY AND OSCILLATING REGIMES

**Katie Barcak[(a)], Lorenzo Castelli[(a)], Geoff Wehmeyer[(a)]**
[(a)] Rice University, Houston, 77005, USA, kb151@rice.edu

## ABSTRACT

Passive thermal regulation is crucial for thermal management and energy conversion systems. Here, we present a thermomagnetically-actuated device that can regulate temperature in either stationary or oscillating modalities, depending on the thermal boundary conditions. The device leverages the magnetic phase transition of gadolinium to actuate motion of a mobile element and control the thermal contact between conducting surfaces. For isothermal boundary conditions, the thermal regulator behaves as a bistable stationary system with a mobile element that either opens or closes a gap, leading to thermal switch ratio of 34 in vacuum (2 in air) and thermal hysteresis near 5 $^{o}$C.(Castelli et al., 2023). For constant heat flow boundary conditions, the mobile element can exhibit self-oscillations that generate AC temperature profiles with 1 to 3 mHz frequencies from a DC heat flow. We will discuss potential applications of these oscillations for thermal sawtooth waveform generation and improved efficiency thermoelectric energy harvesting.

**Keywords:** Thermomagnetic Devices, Thermal Regulator, Thermomagnetic Oscillations

**References:**

Castelli, L., Garg, A., Zhu, Q., Sashital, P., Shimokusu, T.J., & Wehmeyer, G. (2023) ‘A thermal regulator using passive all-magnetic actuation’, *Cell Reports Physical Science*, 4(9), p. 101556. doi:10.1016/j.xcrp.2023.101556.

**Acknowledgement:** This work was supported by an Early Career Faculty grant from NASA’s Space Technology Research Grants Program (Grant #80NSSC20K0066). The research was performed under an appointment to the Building Technologies Office (BTO) IBUILD- Graduate Research Fellowship administered by the Oak Ridge Institute for Science and Education (ORISE) and managed by Oak Ridge National Laboratory (ORNL) for the U.S. Department of Energy (DOE).

*ORAL PRESENTATIONS*

## S08 Mechanocalorics & Thermomechanics KOSOVEL HALL

Chair **Suxin Qian** · Co-chair **Adriana Greco** · Help **Adam Plantarič**

11:30 A multi-transformation temperature approach for a three-stage elastocaloric cooling system
**Het Mevada** · *University of Maryland*

11:42 Development of a novel product-oriented modular elastocaloric cooling system for industrial and life-science applications
**Philipp Molitor** · *Saarland University*

11:54 Operating strategy optimisation for non-holding-step regenerative elastocaloric systems
**Zexi Li** · *The Hong Kong University of Science and Technology*

12:06 Innovative approach to enhancing performance of rotary elastocaloric machines through airflow separation
**Ivan Trofimenko** · *Saarland University*

12:18 Evaluation of a Cu-based elastocaloric alloy for ultra-low temperature cooling
**Pau Giménez-Prades** · *Universitat Jaume I*

12:30 Defining fatigue-life limits of elastocaloric Ni-Ti alloy
**Jan Cerar** · *FME, University of Ljubljana*

12:42 Exploring the elastocaloric potential of NiMnTi alloys
**Francesca Villa** · *CNR ICMATE*

12:54 Development of Fe-modified NiTi shape memory alloys with enhanced cryogenic elastocaloric response
**Giorgia Lupi** · *Politecnico di Milano*

13:06 Mechanocaloric effects in silicone rubber
**Aleix Abadia** · *University of Barcelona*

13:18 Advancing mechanocaloric cooling solutions through 3D printing of superelastic lattice structures
**Francesca Villa** · *CNR ICMATE*

# A MULTI TRANSFORMATION TEMPERAUTRE APPROACH FOR A THREE-STAGE ELASTOCALORIC COOLING SYSTEM

**Het Mevada[(a)], Boyang Liu[(b)], Parham Kabirifar[(b)], Yunho Hwang[(a)], Ichiro Takeuchi[(b)]**

[(a)]Center for Environmental Energy Engineering, Department of Mechanical Engineering, University of Maryland, College Park, Maryland, 20742, United States

[(b)]Department of Materials Science and Engineering, University of Maryland, College Park, Maryland, 20742, United States

*Corresponding author: Tel: (301) 405-6809, E-mail: takeuchi@umd.edu

## ABSTRACT

Elastocaloric systems have emerged as a promising alternative to conventional vapor-compression refrigeration among solid-state cooling technologies. In active regenerative elastocaloric systems, shape memory alloys (SMAs) serve as both the working material and the regenerative heat exchanger. However, strain maldistribution can limit their performance. This work presents a numerical simulation framework to optimize a staggered, multi-stage elastocaloric cooling system. By optimizing the austenite finish temperature ($A_f$) of SMA across the three-stage regenerator, the system achieved a 25% reduction in input work with significantly improved strain uniformity compared to a uniform $A_f$ design. The optimized configuration delivered a giant temperature lift of 42 K, a maximum cooling power of 100 W, and a regenerator-level COP of 7. These results demonstrate that multi transformation temperature elastocaloric regenerators can effectively mitigate the strain inhomogeneities and broaden the operational temperature window, advancing the development of durable, energy-efficient solid-state cooling technologies.

**Keywords:** elastocaloric cooling, shape memory alloy, transformation temperature, numerical modeling

**Acknowledgement:** The authors gratefully acknowledge the support of this effort from the National Science Foundation under award number ERC-2330175 for the Engineering Research Center EARTH.

# DEVELOPMENT OF A NOVEL PRODUCT-ORIENTED MODULAR ELASTOCALORIC COOLING SYSTEM FOR INDUSTRIAL AND LIFE-SCIENCE APPLICATIONS

**Philipp Molitor[a,b], Franziska Louia[a], Stefan Seelecke[a], Paul Motzki[a,b]**

[a] Saarland University, Department of Systems Engineering,
Saarbruecken, 66123, Germany, philipp.molitor@uni-saarland.de

[b] Center for Mechatronics and Automation Technology (ZeMA gGmbH), Saarbruecken, 66121, Germany

## ABSTRACT

Elastocaloric cooling constitutes a promising solid-state refrigeration technology with considerable potential for integration into compact life-science instrumentation requiring sustainable and precise thermal management. By cyclically conditioning a confined air volume within a closed-loop configuration, the system attains high thermodynamic efficiency while avoiding the use of environmentally harmful refrigerants. To simplify maintenance and reduce operational downtime, the central elastocaloric module is designed as an easily interchangeable component. This modular design approach enables a compact and scalable cooling solution tailored for highly sensitive life-science applications.

This study presents the development of the final design concept for the first product-oriented elastocaloric cooling unit and investigates its functional principles and operational characteristics. The performance of the NiTi-wire-based system is experimentally evaluated and correlated with the outcomes of the preceding design phase and numerical simulations.

**Keywords:** Elastocalorics, Elastocaloric Device, Fully Modular, Interchangeable EC Unit, Application, Life-Science

**References:** S.-M. Kirsch, M. Schmidt, F. Welsch, N. Michaelis, A. Schütze, and S. Seelecke, "Development of a shape memory based air conditioning system," in Engineering for a Changing World: Proceedings; 59th IWK, Ilmenau Scientific Colloquium, Technische Universität Ilmenau, September 11-15, 2017, Ilmenau, 2017. [Online] urn:nbn:de:gbv:ilm1-2017iwk-046:4

**Acknowledgement:** The author gratefully acknowledges the support provided by technotrans SE and mateligent GmbH in the framework of this research work.

# OPERATING STRATEGY OPTIMIZATION FOR NON-HOLDING-STEP REGENERATIVE ELASTOCALORIC SYSTEMS

**Zexi Li, Guoan Zhou, Shuhuai Yao**

Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology
Hong Kong, China, e-mail meshyao@ust.hk

## ABSTRACT

Active regeneration is typically used to increase the temperature span of elastocaloric (eC) devices. A roller- cam-driven elastocaloric refrigerator can reduce the system complexity as it operates continuous loading and unloading steps without pausing/holding for working fluid convection. Thus, mechanical and thermal phase synchronization is crucial for performance optimization. This study investigates the phase difference between the loading and thermal cycles by 3D numerical simulation. At 0.5 Hz and a utilization factor V* = 1, a ¼-cycle shift increases the no-span specific cooling power by 9.9 times and the no-load temperature span by 3.1 times compared to the fully synchronous case.

**Keywords:** elastocaloric; 3D simulation; active regeneration

**References:**

Qian S, Catalini D, Muehlbauer J, Liu B, Mevada H, Hou H, et al. High-performance multimode elastocaloric cooling system. Science 2023;380:722–7. https://doi.org/10.1126/science.adg7043.

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Zhou G, Li Z, Wang Q, Zhu Y, Hua P, Yao S, et al. A multi-material cascade elastocaloric cooling device for large temperature lift. Nat Energy 2024:1–9. https://doi.org/10.1038/s41560-024-01537-3.

Zhou G, Zhang L, Li Z, Hua P, Sun Q, Yao S. Achieving kilowatt-scale elastocaloric cooling by a multi-cell architecture. Nature 2025;639:87–92. https://doi.org/10.1038/s41586-024-08549-9.

**Acknowledgement:** This work is financially supported by the General Research Fund (Grant No. 16204422) and Strategic Topics Grant (Grant No. STG2/E- 605/23-N) under the Hong Kong Research Grant Council, and the Innovation and Technology Support Program (Mid-stream, theme-based) under the Innovation and Technology Fund (Grant No. ITS/030/22MS).

# INNOVATIVE APPROACH TO ENHANCING PERFORMANCE OF ROTARY ELASTOCALORIC MACHINES THROUGH AIRFLOW SEPARATION

**Ivan Trofimenko[(a)(b)], Lukas Ehl[(b)], Franziska Louia[(a)], Paul Motzki[(a)(b)]**

[(a)] Saarland University, Department of Systems Engineering Saarbruecken, 66123, Germany,
ivan.trofimenko@uni-saarland.de

[(b)] Center for Mechatronics and Automation Technology (ZeMA gGmbH), Saarbruecken, 66121, Germany

## ABSTRACT

The elastocaloric effect offers great potential for the development of environmentally friendly and sustainable solid-state heating and cooling machines. In the previously introduced rotary elastocaloric machines with tension loaded elements cooling and heating of SMA wires takes place in different portions of the same channel, mixing of cooled and heated air is therefore possible. For maximizing heating and/or cooling performance this mixing has to be deminished. Instead of using additionally actuated locks for airflow division it's preferrable to separate the airflow between cooling and heating portions by means of stationary channel walls of an optimized shape. An innovative approach for flow separation has been proposed, examined with CFD simulations and applied in presented air-based machine with inner cooling volume. Experimental data measured on hardware prototype has been used to adjust the FEM model to account for additional effects, explanation of these effects has also been quantitatively examined.

**Keywords:** elastocaloric effect, EC-machines, performance enhancement, CFD, airflow optimization

**References:**

Ehl, L. et al. (2025), Elastocaloric can cooler: an exemplary technology transfer to use case application. *Frontiers in Materials 12*. Doi:10.3389/fmats.2025.1563997

Kirsch, S. M. et al. (2018). NiTi-based elastocaloric cooling on the macroscale: from basic concepts to realization. *Energy Tech. 6*, 1567–1587. doi:10.1002/ente.201800152

# EVALUATION OF A CU-BASED ELASTOCALORIC ALLOY FOR ULTRA-LOW TEMPERATURE COOLING

**Pau Giménez-Prades*[(a)], Žiga Ahčin[(b)], Andrej Žerovnik[(b)], Tomaž Pšeničnik[(b)], Joaquín Navarro-Esbrí[(a)], Adrián Mota-Babiloni[(a)], Jaka Tušek[(b)]**

[(a)] ISTENER Research Group, Department of Mechanical Engineering and Construction, Universitat Jaume I, Castelló de la Plana, 12071, Spain

[(b)] Faculty of Mechanical Engineering, University of Ljubljana, Ljubljana, 1000, Slovenia

*Corresponding author: pgimenez@uji.es, +34 651526798

## ABSTRACT

Elastocaloric refrigeration is regarded as one of the most promising next-generation non-vapour-compression cooling technologies. Although most research efforts have focused on investigating elastocaloric materials and systems operating near room temperature, the development of solutions capable of functioning at ultra-low temperatures remains highly desirable for applications such as biomedical refrigeration or liquefied-gas storage. For this reason, this work investigates a Cu-based shape memory alloy (SMA) for elastocaloric cooling at ultra-low temperatures. First, a series of isothermal and adiabatic tests is performed to characterize the material experimentally. Experimental characterization revealed a reproducible elastocaloric effect at temperatures down to −60°C, with a 10 K temperature change and low hysteresis, demonstrating its potential for ultra-low temperature elastocaloric devices. The resulting elastocaloric data serve as input for a cascade vapour-compression–elastocaloric model used to evaluate cooling performance at ultra-low temperatures.

**Keywords:** Elastocaloric cooling, Shape memory alloy, Modelling, Ultra-low temperature

# DEFINING FATIGUE-LIFE LIMITS OF ELASTOCALORIC NI-TI ALLOY

**Jan Cerar[(a)], Jernej Klemenc[(a)], Jaka Tušek[(a)]**

(a) University of Ljubljana, Faculty of Mechanical Engineering
1000 Ljubljana, Slovenia, e-mail: jan.cerar@fs.uni-lj.si

## ABSTRACT

As global demand for environmentally sustainable cooling grows, elastocaloric systems have emerged as compelling candidates to replace traditional vapor-compression technologies. Their success, however, hinges on overcoming the intrinsic fatigue limitations of elastocaloric materials under tensile stress. Although tensile loading enables thin, slender elements with fast and efficient heat transfer, it is also more susceptible to fatigue damage. Defining optimal operating conditions—specifically mean strain and strain amplitude—is therefore essential for ensuring fatigue-resistant operation and can lead to performance characteristics that deviate from conventional expectations. Here, the fatigue behavior of a superelastic NiTi alloy was systematically investigated under various mean and amplitude strains, both for compressive and tensile loading regimes, while simultaneously monitoring the elastocaloric effect. The resulting 3D Haigh-like (in)finite-life diagram, constructed from strain and corresponding adiabatic temperature changes, identifies loading regions that enable continuous, fatigue-resistant operation with sufficiently large temperature changes for effective elastocaloric cooling and heat-pumping applications.

**Keywords:** elastocaloric effect, fatigue life, compression, tension

**Acknowledgement:** This work was supported by the European Research Council under the Horizon 2020 program (ERC starting grant no. 803669).

# EXPLORING THE ELASTOCALORIC POTENTIAL OF NIMNTI ALLOYS

**Francesca Villa[a,b*], Emanuele Bestetti[a], Zejun Deng[b], Lara Righi[c], Daniel Salazar[d], Nicola Bennato[a], Francesca Passaretti[a], Riccardo Casati[b], Elena Villa[a]**

[a]CNR ICMATE, Via Previati 1/E, 23900, Lecco, Italy (francesca.villa@cnr,it; emanuelebestetti@cnr.it; nicola.bennato@cnr.it; francesca.passaretti@cnr.it; elena.villa@cnr.it)

[b]Politecnico di Milano, Department of Mechanical Engineering, Via privata La Masa 1, 20156 Milano, Italy (zejund@nwpu.edu.cn; riccardo.casati@polimi.it)

[c]Università degli studi di Parma, Dipartimento di Scienze Chimiche, della Vita e della Sostenibilità Ambientale, Parco Area delle Scienze 17/A, 43124 Parma, Italy (lara.righi@unipr.it)

[d]BCMaterials, Basque Center for Materials, Applications and Nanostructures, EHU Science Park, 48940 Leioa, Spain (daniel.salazar@bcmaterials.net)

* Corresponding author: francesca.villa@cnr,it , +39 3281731848

## ABSTRACT

The use of caloric materials for solid-state-cooling applications presents a sustainable alternative to traditional vapor compression-based refrigeration methods. Among elastocaloric materials, superelastic shape memory alloys stand out, owing to the reversible stress-induced martensitic transformation which involves high latent heat. NiMnTi-based alloys show remarkable elastocaloric performance due to the large unit cell volume change during martensitic transition and to their promising mechanical properties. In this work, polycrystalline NiMnTi alloys were produced through different casting methods and the correlation between process conditions and microstructural, thermal and mechanical properties was investigated. The mechanical characterization was the core of the work: both isothermal and quasi-adiabatic mechanical tests were performed alongside strain recovery measurements, to determine the elastocaloric parameters of NiMnTi alloys produced through different methods. The current study contributes to the expansion of the knowledge on polycrystalline NiMnTi alloy produced through cost-effective processes to lay the foundations for further development of effective elastocaloric alloys.

**Keywords:** NiMnTi, Arc melting, Melt spinning, Suction casting, elastocaloric effect, mechanical properties

**References:**

Villa, F. et al. (2024) 'Effect of the thermal processing on the microstructural, functional and mechanical properties of cast polycrystalline NiMnTi alloys', Journal of Alloys and Compounds, 1000, 175099, https://doi.org/10.1016/j.jallcom.2024.175099 ;

Villa, F. et al. (2024) 'Direct and indirect assessment of the elastocaloric properties of cast NiMnTi alloys', Journal of Alloys and Compounds, 1010, 177570, https://doi.org/10.1016/j.jallcom.2024.177570

# DEVELOPMENT OF FE-MODIFIED NITI SHAPE MEMORY ALLOYS WITH ENHANCED CRYOGENIC ELASTOCALORIC RESPONSE

**G. Lupi[a*], F. Galli[a], E. Bestetti[b], A. Nespoli[b], S. Bonati[b], E. Villa[b], R. Casati[a]**

[a]Department of Mechanical Engineering, Politecnico di Milano, 1 Via Privata Giuseppe La Masa, 20156 Milano, Italy

[b]Consiglio Nazionale delle Ricerche Istituto per la Materia Condensata e Tecnologie per l'Energia (CNR ICMATE, Sede di Lecco, Via G. Previati 1/E, 23900 Lecco, Italy

*e-mail: giorgia1.lupi@polimi.it; phone number: +39 3343121604

## ABSTRACT

Shape memory alloys (SMAs) are among the most promising materials for solid-state cooling due to their large elastocaloric effect (eCE) associated with the stress-induced martensitic transformation. In this work, the effect of Fe addition (3–5 at.%) on NiTi-based SMAs was investigated to enhance their eCE performance. Bulk samples were produced by arc melting, while ribbons were obtained through hot and subsequent cold working steps. Both were heat-treated according to different schedules to tailor their microstructure and transformation behavior. Comprehensive microstructural analyses were performed to correlate phase evolution, grain size, texture, and secondary phase distribution with alloy composition and thermal treatment, and to evaluate their effect on functional and mechanical properties. Increasing Fe content progressively lowers the transformation temperatures, while heat treatments further tune the phase stability. Compression and tensile tests were also conducted to assess the mechanical response and elastocaloric properties.

**Keywords:** Shape memory alloys; NiTi, Elastocaloric effect;

**Acknowledgement:** The authors acknowledge the Ministry of University for funding the project "Improved elastoCaloric Effect BEyond tRaditional thermal manaGement (ICEBERG)" under the framework of the programme PRIN (Progetti di Rilevante interesse Nazionale) Prot. 2022LB2LSZ

# MECHANOCALORIC EFFECTS IN SILICONE RUBBER

**Aleix Abadia-Huguet[a,b], Pol Barcelona[d], Mariona Roura-Bosch[d], Eduard Vives[a,b], Elena Xuriguera[d], Lluís Mañosa[a,c], Klara Lünser [a,e], Enric Stern-Taulats[a,c]**

[a] Departament de Física de la Matèria Condensada,Univeristat de Barcelona 08028, Barcelona, Catalunya.

[b] Univeristat de Barcelona Institut of Complex Systems (UBICS) ,08028, Barcelona Catalunya.

[c] Institut de Nanociència i Nanotecnología (IN2UB), 08028, Barcelona Catalunya.

[d] DIOPA Research Group, Departament de Ciència de Materials i Química Física, Univeristat de Barcelona, 08028, Barcelona, Catalunya.

[e] Institute for Energy and Materials Processes – Applied Quantum Materials (AQM), University Duisburg-Essen,47057, Duisburg, Germany.

## ABSTRACT

Polymeric mechanocaloric materials can provide cooling at low values of the applied force (Fan et al., 2025). While it is well known that the elastocaloric response in natural rubber arises near it strain-driven chrystallisation , silicone rubber materials have received limited attention despite their wide use and ease of manufacturing (Ohlberg et al., 1958),(Xie et al., 2016). To date, only one study has little examined its elastocaloric behavior at room temperature (Bennacer et al., 2021), while another has reported giant barocaloric effects under pressure (Imamura et al., 2020). In this work, we present a comprehensive characterization of the mechanocaloric response of Silicone Rubber to gain insight in its physical origins. The elastocaloric effect was studied at room temperature using infrared thermography, and over a broader temperature range using indirect methods based on Maxwell relations under both tensile and compressive modes. In-situ X-ray diffraction was employed to correlate macroscopic caloric effects with microscopic structural evolution under tensile stress. Finally, results on the uniaxial response are compared with a characterisation of the barocaloric counterpart, thus providing the full mechanocaloric description frame.

**Keywords:** Polymers, Silicone Rubber, Elastocaloric, Barocaloric, X-Ray.

**References:**

Bennacer, R., Liu, B., Yang, M. and Chen, A. (2021) ‘Refrigeration performance and the elastocaloric effect in natural and synthetic rubbers’, *Applied Thermal Engineering*, 204, article 117938. doi: 10.1016/j.applthermaleng.2021.117938.

Fan, X., Chen, S., Manshaii, F., Duan, Z., Chen, G., Zhao, X., Zhou, Y. and Chen, J. (2025) ‘Advances in soft mechanocaloric materials’, *Advanced Functional Materials*. doi: 10.1002/adfm.202420997.

Imamura, W., Usuda, É.O., Paixão, L.S., Bom, N.M., Gomes, A.M. and Carvalho, A.M.G. (2020) ‘Supergiant barocaloric effects in acetoxy silicone rubber over a wide temperature range: great potential for solid-state cooling’, *Chinese Journal of Polymer Science*, 38, pp. 999–1005. doi: 10.1007/s10118-020-2423-9.

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Xie, Z., Sebald, G. and Guyomar, D. (2016) ‘Comparison of direct and indirect measurement of the elastocaloric effect in natural rubber’, *Applied Physics Letters*, 108(4), article 041901. doi: 10.1063/1.4940378.

# ADVANCING MECHANOCALORIC COOLING SOLUTIONS THROUGH 3D PRINTING OF SUPERELASTIC LATTICE

**Emanuele Bestetti[(a)], Francesca Villa[(a)], Elena Villa[(a)], Ehsan M. Shirkharkolaei[(b)], Shirin Dehgahi[(b)], Davoud Jafari[(b)]**

[(a)] CNR ICMATE, Lecco, 23900, Italy, emanuelebestetti@cnr.it

[(b)]University of Twente, Enschede, 7500 AE, Netherlands, davoud.jafari@utwente.nl

## ABSTRACT

Shape Memory Alloys (SMAs) are materials that undergo a first-order phase transformation upon mechanical deformation. The variation of latent heat associated with the Thermoelastic Martensitic Transformation (TMT) enables caloric effects that can be exploited in cooling applications. Laser powder bed fusion (LPBF), an additive manufacturing technique, allows the manufacturing of complex architectures with large exchange surface area. In particular, struts-based lattice structures not only enhance the heat exchange but also improve the stress-induced TMT while maintaining their structural integrity. Moreover, it is also possible to introduce compositional or microstructural gradients which can further enhance the mechanocaloric efficiency and the temperature window. In our work, we fabricated NiTi and/or NiMnTi lattice structures with LPBF. The mechanocaloric properties are investigated experimentally upon unidirectional compression and torsional deformation. Factors influencing the functional performances of the material are considered and eventually characterized. Moreover, the mechanical properties and cycling resistance were assessed.

**Keywords:** Mechanocaloric effect; NiTi; NiMnTi; Lattices; Laser Powder Bed Fusion

## S09 Magnetocalorics & Thermomagnetics LINHART HALL

Chair **Katja Klinar** · Co-chair **João Silva** · Help **Kamyar Dobakhti**

14:30 Magnetostructural insights in multiphase high-entropy alloys via advanced thermomagnetic characterisation and microscopy
**Jia-Yan Law** · *University of Seville*

14:42 Rotating magnetocaloric effect of textured ycrystalline $RNi_5$ in medium magnetic fields (up to 2 T)
**Yurii Koshkidko** · *ILT&SR, Polish Academy of Sciences*

14:54 Rotating magnetocaloric effect in highly anisotropic epoxy-bonded MnFePSi composite
**João Silva** · *IFIMUP — University of Porto*

15:06 Magnetic reversibility accompanied by thermal hysteresis in magnetocaloric materials: a lock-in thermography study
**Jorge Revuelta-Losada** · *University of Seville*

15:18 A high-throughput study of carbon and copper substitution in gadolinium-based films
**Tchilabalo Pakam** · *Univ. Grenoble Alpes, CNRS, Institut Néel*

15:30 The conventional and rotating magnetocaloric effect of a gadolinium parallel-plate magnetic regenerator — influence of geometry
**Rafael Almeida** · *University of Porto — IFIMUP*

15:42 FEMCE — your one-stop software for 3D magnetocalorics simulation
**Rodrigo Kiefe** · *CICECO — Aveiro Institute of Materials*

15:54 Exploring the critical parameters of the shape anisotropy based rotating magnetocaloric effect in Gd
**Gonçalo Oliveira** · *Universidade do Porto — FCUP / IFIMUP*

16:06 A proposed cycle design for active magnetic regenerators to enhance magnetocaloric heat pump performance
**Kunihiko Hayashi** · *Toyota Motor Corporation*

16:18 Validation of the numerical simulation of a high-frequency regenerative thermomagnetic generator HyperEG
**Kamyar Dobakhti** · *FME, University of Ljubljana*

# MAGNETOSTRUCTURAL INSIGHTS IN MULTIPHASE HIGH-ENTROPY ALLOYS VIA ADVANCED THERMOMAGNETIC CHARACTERIZATION AND MICROSCOPY

**Jia Yan Law[a], Liuliu Han[b], Dierk Raabe[b], Oliver Gutfleisch[c], Victorino Franco[a]**

[a] Multidisciplinary Unit for Energy Science, University of Seville, Spain, jylaw@us.es

[b] Max Planck Institute for Sustainable Materials, Düsseldorf, Germany

[c] Department of Materials Science, Technical University of Darmstadt, Darmstadt, Germany

## ABSTRACT

Third-generation high-entropy alloys (HEAs) are defined by compositions strategically designed from the medium entropy ones to achieve targeted functional properties (Klinar et al., 2024), (Law et al., 2023), (Zhang et al., 2024). The seed of this generation, the FeMnNiGeSi HEAS, are multiphase yet achieve magnetocaloric effect (MCE) exceeding previous results (Law et al., 2021) and competitive with conventional benchmark materials, like $La(Fe,Si)_{13}$, $Fe_2P$, and $Gd_5Si_2Ge_2$, upon low-temperature annealing. This treatment modifies the distribution of magnetic anisotropy, substantially enhancing MCE. These alloys undergo magnetostructural transformations, which are further investigated using temperature-dependent first-order reversal curve (TFORC) analysis and advanced microscopy. This analytical framework enables mapping of phase coexistence and the evolution of hysteresis with both field and temperature. The findings overturn the long-standing single-phase paradigm of HEAs and demonstrate that controlled multiphase character can deliver enhanced functional properties. Reporting TFORC behavior for the first time in any HEA, this work establishes foundational insights to advance the rational design of next-generation magnetocaloric HEAs.

**Keywords:** Magnetocaloric effect; high-entropy alloys; third generation; temperature-dependent first-order reversal curve (TFORC); advanced microscopy.

**References:**

Klinar, K., Law, J.Y., Franco, V., Moya, X. and Kitanovski, A. (2024) ‘Perspectives and energy applications of magnetocaloric, pyromagnetic, electrocaloric, and pyroelectric materials’, *Advanced Energy Materials*, 14, article 2401739. doi: 10.1002/aenm.202401739

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# ROTATING MAGNETOCALORIC EFFECT OF TEXTURED POLYCRYSTALLINE $RNI_5$ IN MEDIUM MAGNETIC FIELDS (UP TO 2 T)

**Yurii Koshkidko[(a)], Jacek Ćwik[(a)], Catalina Salazar Mejia[(b)]**

[(a)] Institute of Low Temperature and Structure Research, Polish Academy of Sciences, Wrocław 50-422, Poland, y.koshkidko@intibs.pl, j.cwik@intibs.pl

[(b)] Hochfeld-Magnetlabor Dresden (HLD-EMFL), Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany, c.salazar-mejia@hzdr.de

## ABSTRACT

Recently, polycrystalline magnetocaloric materials with rotating MCE have attracted more attention due to their more convenient sample preparation than monocrystalline materials (Zhou et al., 2022). In our case, samples of polycrystalline $RNi_5$ with induced magnetic anisotropy were obtained by directional crystallization. Grain orientation was investigated using EBSD. To investigate MCE in medium magnetic fields (up to 1.8 T), we used a magnetic field source based on permanent magnets and an apparatus for direct MCE measurements placed on a rotary table (Koshkid'ko et al., 2017). Measurements were carried out in different directions relative to the main axis of the magnetic texture. As a result of direct measurements of the MCE, it was found that the rotational MCE of polycrystalline $DyNi_5$ in the Curie temperature region (14 K) is 1.2 K at 1.8 T. This value is comparable to the rotational MCE observed previously in single crystals (Nikitin et al., 2010). The influence of magnetocrystalline anisotropy on the magnitude of rotating MCE is discussed.

**Keywords:** rotating MCE, magnetocrystalline anisotropy, directional crystallization, direct method of MCE research, medium magnetic fields

**References:**

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# ROTATING MAGNETOCALORIC EFFECT IN HIGHLY ANISOTROPIC EPOXY-BONDED MNFEPSI COMPOSITE

**João O. Silva[a], Ricardo M. C. Pinto[a], Rafael Almeida[a], A. Descalzo-Ruiz[b], J. Revuelta-Losada[b], V. Franco[b], J.Y. Law[b], R. Kiefe[c], J.S. Amaral[c], N.M. Dempsey[d], Ana L. Pires[a], Gonçalo N. P. Oliveira[a], João H. Belo[a]**

[a] IFIMUP, Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto,
Porto, 4169-007, Portugal, joasilva@fc.up.pt

[b]Multidisciplinary Unit for Energy Science (MUFENS), Departamento de Física de la Materia Condensada, Universidad de Sevilla, Sevilla 41080, Spain

[c]Department of Physics and CICECO, University of Aveiro, Campus of Santiago, Aveiro, 3810-193, Portugal

[d]University Grenoble Alpes, CNRS, Grenoble INP, Institut NEEL, Grenoble, 38000, France

## ABSTRACT

The rotating magnetocaloric effect (RMCE) (Almeida et al., 2024) has triggered attention for its potential in refrigeration devices using low-intensity fields (~0.4 T). Yet, typical magnetocaloric materials (MCMs) Klinar et al., 2024) studied for RMCE still present major challenges: (i) relying on heavy and critical rare earth metals like Gd; (ii) being single crystals or highly textured polycrystals complex to produce; and (iii) being second-order magnetic transition alloys, used to avoid magnetic hysteresis and brittleness (Gutfleisch et al., 2016). Here we address these challenges by developing high-loading MnFePSi epoxy-bonded composites optimized for RMCE. The epoxy was processed in a high aspect ratio mold with up to 98wt% of the inorganic MCM. Composites were cured with and without a magnetic field to induce magnetic anisotropy via particle orientation. RMCE was studied via SQUID-VSM to evaluate the impact of combining a pseudo-magnetocrystalline anisotropy with shape anisotropy. Overall, the approach provides a simple and scalable pathway to engineer high-performance RMCE composites for cooling technologies.

**Keywords:** Composites; MnFePSi; RMCE; Anisotropy

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**Acknowledgement:** This project has received funding from the European Union's Horizon Europe research and innovation programme through the European Innovation Council under the grant agreement No. 101161135 – MAGCCINE

# MAGNETIC REVERSIBILITY ACCOMPANIED BY THERMAL HYSTERESIS IN MAGNETOCALORIC MATERIALS: A LOCK-IN THERMOGRAPHY STUDY

**Jorge Revuelta-Losada[(a)], Aun Nawaz Khan[(a)], Luis M. Moreno-Ramírez[(b)], Jia Yan Law[(a)], V. Franco[(a)]**

[(a)]Multidisciplinary Unit for Energy Science, University of Seville, Dpto. Física de la Materia Condensada, ICMS-CSIC, University of Seville, Seville, 41012, Spain. jrevuelta1@us.es (+34 608700711)

[(b)]Dpto. de Electricidad y Electrónica, University of Valladolid, Valladolid, 47011, Spain.

## ABSTRACT

Direct tracing of the magnetocaloric effect offers insight into the real-world performance, cyclability and heat transfer dynamics of materials for their implementation in efficient magnetic refrigeration devices.

In this work, infrared thermography -a direct, non-contact, high-throughput technique- together with lock-in amplification for enhancing the signal-to-noise ratio, is implemented for systematic characterization and evaluation of the adiabatic temperature change of relevant magnetocaloric material families (Revuelta-Losada et al, 2025). The method enables the simultaneous acquisition of the phase shift with respect the magnetic field oscillations, evidencing the frequency-dependence of the caloric properties, essential to take into account in the regeneration cycle of refrigerators. Furthermore, the application of non-saturating fields (in many cases in the order of those typically used in actual applications) proved the thermal hysteresis of the reversible adiabatic temperature change in different materials despite the transition being reversible vs. field oscillations. Additionally, the method enables the 2D mapping of the caloric effect.

**Keywords:** Magnetocaloric effect; Direct characterization measurements; Lock-in thermography; Hysteresis; Reversibility; Dynamic conditions

**References:**

Revuelta-Losada, J., Khan, A.N., Moreno-Ramírez, L.M., Law, J.Y., Giri, A.K., Franco, V. (2025) ‘Magnetic reversibility accompanied by thermal hysteresis in magnetocaloric materials: A lock-in thermography study’, Materials & Design, 256, p. 114372. doi: 10.1016/j.matdes.2025.114372

**Acknowledgement:** Work funded by PID2023-146047OB-I00 from AEI/10.13039/501100011033, the European Innovation Council, funded by the European Union, via project Magccine (Grant agreement 101161135), the Clean Hydrogen Partnership and its members within the project HyLICAL (Grant No. 101101461), project PPIT2024-31833, co-financed by EU, Ministerio de Hacienda y Función Pública, FEDER and Junta de Andalucía, and VII Plan Propio de Investigación from University of Seville. J.Y.L acknowledges EMERGIA 2021 fellowship from Junta de Andalucía (Ref. EMC21_00418).

# A HIGH THROUGHPUT STUDY OF CARBON AND COPPER SUBSTITUTION IN GADOLINIUM BASED FILMS

**Tchilabalo Pakam[(a)], P. Le Berre[(a)], W. Rigaut[(a)], L. Fink[(a)], R. Haettel[(a)], Ewen Bellec[(a)], Nils Blanc[(a)], Thibaut Deviller[(a)], João H. Belo[(b)] and Nora M. Dempsey[(a)]**

[(a)] Univ. Grenoble Alpes, CNRS, Institut Néel,

Grenoble, 38000, France, tchilabalo.pakam@neel.cnrs.fr

[(b)] IFIMUP, Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Porto, 4169-007, Portugal

## ABSTRACT

A combinatorial thin-film approach was employed to investigate the tunability of magnetic, magnetocaloric, and structural properties of compositionally graded GdX (X = C, Cu) films synthesized by high-rate triode sputtering. High-throughput characterization of the graded films was carried out across 100 mm wafers using EDX spectroscopy, mechanical profilometry, SEM, XRD (both lab and synchrotron-based), and MOKE magnetometry, complemented by SQUID-VSM M(H,T) measurements on selected samples. The Curie temperature ($T_C$), saturation magnetization and crystallographic texture were shown to be influenced by element substitution, deposition temperature, and post-deposition annealing. These findings demonstrate how rapid screening enables an accelerated exploration and optimization of Gd-based magnetocaloric materials for next-generation solid-state cooling technologies.

**Keywords:** [Magnetocaloric Materials, Gd based films, Combinatorial approach]

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# THE CONVENTIONAL AND ROTATING MAGNETOCALORIC EFFECT OF A GADOLINIUM PARALLEL PLATE MAGNETIC REGENERATOR - INFLUENCE OF GEOMETRY

**Rafael Almeida[(a)], Rodrigo Kiefe[(b)], Darja Gačnik[(c)], Ricardo M. C. Pinto[(a)], João O. Silva[(a)], Katja Klinar[(c)], Henrique Souza[(b)], Gonçalo Oliveira[(a)], João S. Amaral[(b)], Andrej Kitanovski[(c)], João H. Belo[(a),*]**

[(a)]IFIMUP – Institute of Physics for Advanced Materials, Nanotechnology and Photonics, Department of Physics and Astronomy, Faculty of Sciences of University of Porto, Rua do Campo Alegre, 687, 4169-007 Porto, Portugal

[(b)]Physics Department and CICECO — Aveiro Institute of Materials, University of Aveiro, 3810-193 Aveiro, Portugal

[(c)]Faculty of Mechanical Engineering, University of Ljubljana, Askerceva 6, Ljubljana 1000, Slovenia

*jbelo@fc.up.pt

## ABSTRACT

Most magnetic refrigerators rely on the conventional magnetocaloric effect (MCE), where magnetocaloric materials exhibit temperature change when exposed to variations in magnetic field intensity. Recently, it has been shown that demagnetizing effects in anisotropically shaped samples can give rise to the rotating magnetocaloric effect (RMCE) when either the sample or the magnetic field is rotated, potentially enabling more compact and efficient magnetic refrigeration devices (Almeida, et al., 2024), (de Souza et al., 2025).

The RMCE was investigated in assemblies of parallel plates tapered into cylindrical tubing through finite element simulations, determining the internal field profile induced by different external magnetic fields (Kiefe and Amaral, 2025). By varying plate thickness, width, length, spacing, and total number of plates, we find that increasing the number of plates is a key parameter, enhancing the total available $\Delta S_{iso}$ while reducing the maximum $\Delta T_{ad}$. This trade-off, driven by greater refrigerant mass and stronger inter-plate magnetic interactions, motivated a systematic study of RMCE-based active magnetic regenerators.

**Keywords:** Magnetic Refrigeration, Rotational Magnetocaloric Effect

**References:**

Almeida, R. et al. (2024) ‘Rotating magnetocaloric effect in polycrystals—harnessing the demagnetizing effect’, *J. Phys. Energy* **6** 015020. https://doi.org/10.1088/2515-7655/ad1c61

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# FEMCE – YOUR ONE-STOP SOFTWARE FOR 3D MAGNETOCALORICS SIMULATION

**Rodrigo Kiefe[(a)], Henrique Souza[(a)], João Amaral[(a)]**

[(a)] Department of Physics and CICECO - Institute of Materials, Aveiro, 3810-193, Portugal, ciceco@ua.pt

## ABSTRACT

We present new capabilities and features of our in-house software FEMCE (Kiefe and Amaral, 2025), a user-friendly 3D Finite Element simulation tool. As an example, the magnetic cooling performance (heterogeneous heat and temperature change) of key refrigerant designs are evaluated and characterized with FEMCE, such as: a stack of evenly spaced thin plates, packed beds and micro-channeled refrigerants. These refrigerant designs are then evaluated considering different benchmark materials, exhibiting both first- and second-order magnetic phase transitions. FEMCE streamlines studies on a recent emerging alternative approach to induce magnetic cooling based on the shape anisotropy of the refrigerant (Almeida et al., 2024). Using FEMCE, the conventional approach to magnetic cooling is challenged, showcasing the performance benefits of this demagnetizing field-based magnetocaloric effect, for a wide temperature-span and lower magnetic fields.

**Keywords:** Finite-Element-Method; Magnetocalorics; Demagnetizing field

**References:**

Kiefe, R. and J. S. Amaral (2025) 'FEMCE – A 3D finite element simulation tool for magnetic refrigerants", *International Journal of Refrigeration* 173 pp. 180-184. DOI: 10.1016/j.ijrefrig.2025.02.017

Almeida, R. (2024) 'Rotating magnetocaloric effect in polycrystals – harnessing the demagnetizing effect', *Journal of Physics: Energy* 6 (1). DOI: 10.1088/2515-7655/ad1c61

**Acknowledgement:** This work was developed within the scope of the project CICECO-Aveiro Institute of Materials, UIDB/50011/2020, UIDP/50011/2020 & LA/P/0006/2020, financed by national funds through the FCT/MCTES (PIDDAC), and project PTDC/EME-TED/3099/2020. This work has received funding from the European Union's Horizon Europe research and innovation program through the European Innovation Council under the grant agreement No. 101161135 - MAGCCINE.

# EXPLORING THE CRITICAL PARAMETERS OF THE SHAPE ANISOTROPY BASED ROTATING MAGNETOCALORIC EFFECT IN GD

**Ricardo Pinto[(a)], Rafael Almeida[(a)], João Silva[(a)], Jorge Revuelta-Losada[(b)], Victorino Franco[(b)], Jia Yan Law[(b)], Henrique Souza[(c)],Rodrigo Kiefe[(c)], João Amaral[(c)], Nora Dempsey[(d)], Ana Pires[(a)], Gonçalo Oliveira[(a)], João Ventura[(a)], João Araújo[(a)], João Belo[(a)]**

[(a)] IFIMUP, Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Porto, 4169-007, Portugal, ricpinto@fc.up.pt

[(b)]Multidisciplinary Unit for Energy Science (MUFENS), Departamento de Física de la Materia Condensada, Universidad de Sevilla,Sevilla 41080, Spain

[(c)]Department of Physics and CICECO, University of Aveiro, Campus of Santiago,Aveiro, 3810-193, Portugal

[(d)]University Grenoble Alpes, CNRS, Grenoble INP, Institut NEEL, Grenoble, 38000, France

## ABSTRACT

The rotating magnetocaloric effect (RMCE) consists of a temperature change induced in a material when it is rotated within a constant external magnetic field, eliminating the need for field intensity modulation. Traditionally this effect is studied in systems with strong magnetocrystalline anisotropy (MCA), such as single crystals (Nikitin et al., 2010), and textured polycrystals (Zhang et al., 2015), whose fabrication complexity and cost hinders their practical application. Recently, shape anisotropy (SA) (Almeida et al., 2024),(Quim et al., 2023) has emerged as an alternative mechanism for RMCE, allowing for the use of polycrystals. In this work the critical parameters of the SA-based RMCE are explored in Gd square plates with varying aspect ratios, both directly and indirectly as a function of rotation angle, magnetic field intensity and temperature. Additionally, the experimental results are validated through finite element simulations on the FEMCE software (Kiefe and Amaral, 2025), allowing for the study of the angular dependence of the RMCE and its upper limits.

**Keywords:** Shape Anisotropy; Rotating Magnetocaloric Effect; Gadolinium; Finite Elements

**References:**

Almeida, R., Freitas, S.C., Fernandes, C.R., R Kiefe, Araújo, J.P., Amaral, J.S., Ventura, J.O., Belo, J.H. and Silva, D.J. (2024). Rotating magnetocaloric effect in polycrystals—harnessing the demagnetizing effect. Journal of Physics Energy, 6(1), pp.015020–015020. doi:https://doi.org/10.1088/2515-7655/ad1c61

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# A PROPOSED CYCLE DESIGN FOR ACTIVE MAGNETIC REGENERATORS TO ENHANCE MAGNETOCALORIC HEAT PUMP PERFORMANCE

**Kunihiko Hayashi[a], Daiki Endo[b], Tsuyoshi Kawanami[c]**

[a] HigashiFuji Technical Center, Toyota Motor Corporation

1200, Mishuku, Susono-shi, Shizuoka 410-1193 Japan, kunihiko_hayashi@mail.toyota.co.jp

[b] Graduate School of Science and Technology, Meiji University

1-1-1 Higashi-Mita, Tama-ku, Kawasaki-shi, Kanagawa 214-8571 Japan, ce252051@meiji.ac.jp

[c] Department of Mechanical Engineering Informatics, Meiji University

1-1-1 Higashi-Mita, Tama-ku, Kawasaki-shi, Kanagawa 214-8571 Japan, kawanami@meiji.ac.jp

## ABSTRACT

With the growing demand for energy-efficient refrigeration technologies, magnetocaloric heat pumps have attracted considerable attention. In this study, we focus on magnetic refrigeration technology, which offers high theoretical efficiency, and conduct a fundamental investigation aiming to derive a new cycle configuration suitable for future vehicle applications. In conventional AMR heat exchange processes, the heat transfer fluid reciprocates within the magnetocaloric material (MCM), leading to mixing between the heated and cooled fluid streams, which reduces the effective temperature gradient and consequently deteriorates the overall performance. In the proposed cycle, coolant flows unidirectionally through the MCM, and an additional thermal circuit is incorporated to promote heat transfer and heat dissipation. As a result, the system achieves high-efficiency, greater output, and low-pumping losses. The MCM employed in this work is based on gadolinium ingots, the feasibility is verified through both numerical simulations and experimental demonstration using a prototype device.

**Keywords:** magnetocaloric heat pump, AMR, MCM

**References:**

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# VALIDATION OF THE NUMERICAL SIMULATION OF A HIGH-FREQUENCY REGENERATIVE THERMOMAGNETIC GENERATOR HYPEREG

**Kamyar Dobakhti[(a)], Katja Klinar[(a)], Urban Tomc[(a)], Jure Javornik[(a)], Andrej Kitanovski*[(a)]**

[(a)] University of Ljubljana, Faculty of Mechanical Engineering
Ljubljana, 1000, Slovenia.
andrej.kitanovski@fs.uni-lj.si

## ABSTRACT

As in magnetocaloric devices, thermomagnetic devices also require an increase in operating frequency to enhance their performance. In this paper we present a novel design and numerical validation process of a high-frequency regenerator - the Hypereg (Kitanovski et al., 2023), (Klinar et al., 2024) - for efficient thermo-magnetic energy generation. Hypereg addresses common limitations such as low efficiency, limited operating frequency, high hydraulic losses, fluid mixing, and poor scalability, by introducing multiple parallel regenerators instead of the traditional in-series configuration. This device uses gadolinium plates and four perpendicular uni-directional heat exchangers. This approach enables us to scale the device easily and considerably. Additionally, the shorter fluid travel distance overcomes the limitation of low operating frequency, while the resulting higher frequency, together with the use of heat exchangers, mitigates the low system efficiency. Performance was modeled with an Ansys Fluent numerical model and validated against an experimental prototype, demonstrating the design's scalability and improved operating characteristics. Here we present the validation process and a primary configuration of the device.

**Keywords:** Low-grade waste heat, energy recovery, thermomagnetic energy harvester, heat transfer, magnetocaloric

**References:**

Kitanovski, A., Tomc, U., Klinar, K., Valentinčič, J., Majdič, F., Sabotin, I. & Mencinger, J., 2023. United States Patent. US 12,000,663.

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# TRANSIENT CFD MODELING OF A ROTATIONAL MAGNETOCALORIC REGENERATOR WITH REALISTIC OPERATING CONDITIONS

**Darja Gačnik[(a)], Rafael Almeida[(b)], Rodrigo Kiefe[(c)], Maxime Savary[(d)], Radel Gimaev[(a)], Katja Klinar[(a)], Andrej Kitanovski[(a)]**

(a) University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva 6, 1000 Ljubljana, Slovenia, andrej.kitanovski@fs.uni-lj.si

(b) IFIMUP – Institute of Physics for Advanced Materials, Nanotechnology and Photonics, Department of Physics and Astronomy, Faculty of Sciences of University of Porto, Rua do Campo Alegre, 687, 4169-007 Porto, Portugal, rafael.almeida@fc.up.pt

(c) University of Aveiro, Department of Physics and CICECO – Aveiro Institute of Materials, Campus Universitário de Santiago, 3810-193, Aveiro, Portugal, rodrigokiefe@ua.pt

(d) MagREEsource, 209 Rte des Béalières, 38360 Noyarey, France, maxime.savary@magreesource.com

## ABSTRACT

The rotational magnetocaloric effect (RMCE) provides a promising alternative to conventional MCE by enabling comparable adiabatic temperature changes under lower external magnetic fields (Almeida et al., 2024, Fernandes et al., 2025). It eliminates the need for external magnetic field modulation, as thermodynamic cycle is achieved through rotary-induced changes in the internal magnetic field orientation (Kitanovski et al., 2010). This study presents a transient 2D CFD model of an RMCE-based active magnetic regenerator. The model captures anisotropic heat transfer between the magnetocaloric solid and the fluid, incorporating time-dependent internal field variations generated by different double-Halbach magnet configurations (Vieira et al., 2023),(Fortkamp et al., 2020). A parametric analysis, coupled with a simplified 1D model, investigates magnetic field amplitude, rotation frequency, internal field waveform, and thermal boundary conditions, including finite-capacity reservoirs. Key outputs include spatiotemporal temperature evolution across multiple cycles, reflecting the effectiveness of the heat transfer fluid in extracting and delivering RMCE-generated thermal energy to the external thermal reservoirs, thereby determining net heating and cooling power.

**Keywords:** rotational magnetocaloric effect, active magnetic regenerator, CFD modeling, internal magnetic field variation, solid-state cooling, refrigeration

**References:**

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*ORAL PRESENTATIONS*

## S10 Thermoelectrics & magneto-thermoelectrics

KOSOVEL HALL

Chair **Heiko Reith** · Co-chair **Ran He** · Help **Matija Kalin**

14:30 Microfabricated Si-based µTEG device platform for novel thermoelectric materials
**Llibertat Abad Muñoz** · *IMB-CNM-CSIC*

14:42 Thermal batteries based on hybrid thermionic generators
**Daniele Maria Trucchi** · *Consiglio Nazionale delle Ricerche*

14:54 An innovative heat exchanger with embedded thermoelectric chips for waste cooling recovery
**Ming-chyuan Lin** · *National Taiwan University*

15:06 Magnetic field induced transverse thermoelectric effect in $WSi_2$ single crystal
**Shoya Ohsumi** · *Tokyo University of Science*

# MICROFABRICATED SI-BASED µTEG DEVICE PLATFORM FOR NOVEL THERMOELECTRIC MATERIALS

**Marc Aceituno, A. Rodríguez-Iglesias, Joaquín Santander, Shahadev Rodríguez-Miguel, Iñigo Martín, Luis Fonseca, Llibertat Abad, Marc Salleras**

Institut de Microelectrònica de Barcelona (IMB-CNM-CSIC)

Campus Universitat Autònoma de Barcelona (UAB), E-08193, Cerdanyola del Vallès (Barcelona). Spain

marc.salleras@imb-cnm.csic.es

## ABSTRACT

Waste heat recovery using thermoelectric materials offers a compact, solid-state solution for self-powered devices, especially in harsh environments. While most efforts focus on improving material zT, device design and thermal management are equally critical to maximizing performance. Our group has historically developed silicon-based µTEG platforms integrating nanostructured materials in the form of thin films (Perez-Marín et al., 2014), nanowires (Sojo et al., 2025), and microbeams (Stranz et al., 2022). Here, we present recent advances that increase platform versatility, allowing integration of diverse thermoelectric materials in thin-film form with their specific growth or deposition techniques. To illustrate this, we fabricated and tested a planar silicon µTEG incorporating thin films of $Cr_2Si$ and Nb-doped $SrTiO_3$ (6 mol%), demonstrating the platform's adaptability for evaluating novel thin-film thermoelectric materials integrated into a fully operating device and under realistic operating conditions.

**Keywords:** Silicon, thin film, micro-thermoelectric generator (µTEG), silicide, perovskite.

**References:**

A.P. Perez-Marín et al. nanoEnergy, 4, 73-80 (2014)

J. M. Sojo et al. Adv. Funct. Mat. 35, 2419639 (2025)

A. Stranz et al. Nanomaterials, 12 (8) 1326 (2022)

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# THERMAL BATTERIES BASED ON HYBRID THERMIONIC GENERATORS

**D.M. Trucchi[(a)] on behalf of the BLAZETEC project consortium [(b-g)]**

[(a)] Consiglio Nazionale delle Ricerche – Istituto di Struttura della Materia, Rome, Italy;

[(b)] Universidad Politecnica de Madrid – Instituto de Energia Solar, Madrid, Spain;

[(c)] RGS Development, Amsterdam, The Netherlands;

[(d)] Ionvac Process, Rome, Italy;

[(e)] The Cyprus Institute, Nicosia, Cyprus;

[(f)] Centre Suisse d'Electronique et de Microtechnique, Neuchatel, Switzerland;

[(g)] Thermophoton, Madrid, Spain, e-mail: danielemaria.trucchi@cnr.it

## ABSTRACT

The transition to green energy has led to an increasing demand for advanced battery solutions. The HEU-funded BLAZETEC project (https://blazetec.eu/) aims to develop revolutionary ultra-high-temperature (1200-1600 °C) thermal batteries that offer high-efficiency conversion, cost-effectiveness, and long-duration energy storage. BLAZETEC focuses on the development of a sensible-heat thermal battery for storing concentrated sunlight and providing electric power on demand, and a latent-heat electric thermal battery that can convert surplus electricity from renewables into heat and provide electricity on demand (Datas et al., 2022).

Solid-state thermal-to-electric converters are steady devices with no movement, corresponding to long lifetimes and no necessity of maintenance, and are scalable, with an efficiency not significantly depending on the active size. Batteries under development in BLAZETEC are enabled by advanced solid-state thermal energy converters based on thermionic (TIG), thermoelectric (TEG), and thermophotovoltaic (TPV) generators. Specifically the TIG hybridization is the key technology for efficient high-temperature TIG-TEG (Trucchi et al., 2018) and TIG-TPV (Bellucci et al., 2020, 2022) systems.

**Keywords:** Thermal battery, thermionic energy conversion, thermoelectric generation, thermophotovoltaics, concentrated sunlight, ultra-high temperature

**References:**

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**Acknowledgement:** The BLAZETEC consortium acknowledges the support of the European Commission under grant agreement n. 101160724.

# AN INNOVATIVE HEAT EXCHANGER WITH EMBEDDED THERMOELECTRIC CHIPS FOR WASTE COOLING RECOVERY

**Li-Yuan Chang[a], Mei-Jiau Huang[a], Ming-Chyuan Lin[b], Fu-Tsai Chung [b]**

[a] National Taiwan University,1.1.375V Taipei, 106319, Taiwan, mjhuang@ntu.edu.tw

[b] National Synchrotron Radiation Research Center,
Hsinchu, 300092, Taiwan

## ABSTRACT

A cross-flow heat exchanger embedded with thermoelectric chips is designed for waste cold recovery. The heat exchanger consists of modular flow-channel components. The low-temperature gaseous nitrogen enters the channel next to the cold side of the TEG module as a cold source. After leaving the module, the nitrogen is heated to room temperature by the ambient air, and then guided into the channel next to the hot side of the TEG module as a heat source. Two pairs of parapet walls form an enclosed space between two adjacent flow-channel components, and the thermoelectric chips are installed in these spaces. In addition, the hot nitrogen flow channel is deliberately arranged outside to avoid ice formation on the device surface. An open voltage of 1.4 V and a maximum power generation rate of 22mW are obtained when the flow rate is 110 SLPM.

**Keywords:** Thermoelectric power generation, Waste cold recovery, Heat exchanger, Modular design, Anti-icing

**References:** M.C. Lin, H.Y. Chen, F.T. Chung, M.J. Huang. A design and verification of a non-icing and non-condensing waste-cold-recovery system. https://doi.org/10.1016/j.applthermaleng.2021.117378

**Acknowledgement:** This research was supported by the National Science and Technology Council, Taiwan (Grant No.: NSTC 113-2221-E-002 -189 -MY2).

# MAGNETIC FIELD INDUCED TRANSVERSE THERMOELECTRIC EFFECT IN WSI2 SINGLE CRYSTAL

**Shoya Ohsumi[(a)], Hidetoshi Imai[(a)], Shogo Yoshida[(a)], Yoshiki J. Sato[(b)], Ryuji Okazaki[(a)]**

[(a)]Department of Physics and Astronomy, Tokyo University of Science Noda, 278-8510, Japan, 6224508@ed.tus.ac.jp

[(b)]Graduate School of Science and Engineering, Saitama University Saitama, 338-8570, Japan

## ABSTRACT

Transverse thermoelectric (TTE) conversion generates an electric current orthogonal to the temperature gradient. Because the number of thermal and electrical contacts can be reduced, TTE devices have attracted considerable attention as an efficient approach for thermal management (Uchida, 2022).

In this study, we experimentally demonstrate the TTE effect in $WSi_2$ single crystal under a magnetic field. This material exhibits axis-dependent conduction polarity and has attracted attention as a TTE material in zero magnetic field (Koster, 2023 & Ohsumi, 2024); however, its magnetothermoelectric transport properties have not yet been investigated.

We observe a Nernst effect in this material, where the Nernst thermopower $S_{yx}$ reaches –700 µV/K at 20 K and 6 T. Furthermore, $S_{yx}/T$ shows a distinct peak around 20 K, whereas it becomes constant in the low-temperature range (Behnia, 2016). Through a systematic analysis combined with Hall resistivity, we elucidate that the observed Nernst peak originates from the phonon-drag effect.

**Keywords:** Transverse thermoelectric effect, Nernst effect, axis-dependent conduction polarity, semimetal

**References:**

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**Acknowledgement:** This work was partly supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI via Grants No. 22K20360, No. 22H01166, and No. 24K06945, and the Research Foundation for the Electrotechnology of Chubu (REFEC) via Grant No. R-04102.

## S11 Electrocalorics & Pyroelectrics LINHART HALL

Chair **Xiaoshi Qian** · Co-chair **Emmanuel Defay** · Help **Izak Oberčkal Pluško**

**11:30** Material losses and heat exchanges: a unified thermodynamic approach to cooling efficiency
**Morgan Almanza** · *Université Paris-Saclay*

**11:42** Lead-free pyroelectric energy harvesting
**Moiz Khalil** · *Luxembourg Institute of Science and Technology (LIST)*

**11:54** Power supply for electrocaloric cooling device
**Baron Christophe** · *Université Paris-Saclay*

**12:06** Implementation and validation of an active electrocaloric regenerator component in TCCbuilder
**Grega Belšak** · *FME, University of Ljubljana*

**12:18** Agentic optimisation of thermal conversion system: framework, algorithms and industrial application
**Ahmed Teyeb** · *Brunel University London*

**12:30** Bulk ceramics and aerosol-deposited films for caloric applications
**Hana Uršič** · *Jožef Stefan Institute*

**12:42** Interfacial engineering of electrocaloric polymers for high stability and cooling performance
**Donglin Han** · *The Hong Kong University of Science and Technology*

**12:54** New lead-free Aurivillius oxides for electrocaloric cooling: from bulk to epitaxial thin films
**Sara Lafuerza** · *INMA — CSIC — Universidad de Zaragoza*

**13:06** Direct thermal method reveals high efficiency of electrocaloric lead-free $Ba_{0.6}Sr_{0.4}TiO_3$
**Julius Metzdorf** · *Fraunhofer IPM*

**13:18** Large low-field-driven electrocaloric effect in molecular ferroelectrics
**Yuan Lin** · *Institute of Physics, Chinese Academy of Sciences*

# MATERIAL LOSSES AND HEAT EXCHANGES: A UNIFIED THERMODYNAMIC APPROACH TO COOLING EFFICIENCY

**Morgan Almanza[(a)], Martino LoBue[(a)]**

[(a)] Université Paris-Saclay, ENS Paris-Saclay, CNRS, laboratoire SATIE Gif-sur-yvette, 91190, France,
morgan.almanza@ens-paris-saclay.fr

## ABSTRACT

To achieve highly efficient cooling devices using caloric materials, it is necessary to engineer a system where electric/magnetic field and the heat transfer are fully mastered. The active substance, the source of the field and the thermal switches can all introduce additional losses that need to be considered when estimating the system's efficiency upper bound. At the same time, all cooling systems either use the regenerative approach or they rely on cascade thermodynamic cycles to amplify the temperature variation of the material in order to achieve the required temperature span. The thermodynamic approach we present here provides guidance to understand the regenerative thermodynamic cycle (Brown, 1976; Steyert, 1978) and to design future devices. After describing regenerative and cascaded cycles, the analysis will consider heat transfer within the frame of the finite time thermodynamics. Different approaches for maximizing efficiency will be presented. Finally, additional losses are introduced to illustrate the design challenges.

**Keywords:** cooling, Thermodynamic cycles, losses

**References:**

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# LEAD-FREE PYROELECTRIC ENERGY HARVESTING

**Moiz Khalil**[a, b], **Youri Nouchokgwe**[a], **Emmanuel Defay**[a, b]

[a] Luxembourg Institute of Science and Technology, 5 Av. des Hauts-Fourneaux, 4362 Esch-Belval, Luxembourg

[b] University of Luxembourg, 2 Av. de l'Universite, 4365 Esch-Belval, Luxembourg

E-mail: emmanuel.defay@list.lu, Tel : +352 621 410 452

## ABSTRACT

Pyroelectric generators, which convert temperature fluctuations into electrical energy, are attracting interest in harvesting low grade waste heat. Current high-performance systems often use lead-based materials such as lead scandium tantalate (PST) (Lhertier et al., 2022), which are costly and environmentally unsustainable. We present a lead-free pyroelectric device based on barium strontium titanate (BST) multilayer capacitors (MLCs). BST is an environmentally friendly ferroelectric material with a first order phase transition near room temperature (~18 °C) and lower fabrication costs than PST. A BST MLC prototype was tested under thermal cycling between 0 °C and 115 °C with an applied field of 83 kV $cm^{-1}$ (300 V). At a cycling frequency of 0.36 Hz, corresponding to alternating hot and cold fluid flow, the device delivered an active power density of ~300 W $L^{-1}$, demonstrating efficient thermal-to-electric conversion. BST MLCs are shown to be promising candidates to replace lead-based materials, including PST, for pyroelectric energy harvesting.

**Keywords:** Pyroelectric energy harvesting; Lead-free; Barium strontium titanate; Multilayer capacitors; Sustainable; Active power density.

**Reference :** Lhertier, P., Torelló, A., Usui, T., et al. (2022) 'Large harvested energy with non-linear pyroelectric modules', *Nature*, 609, pp. 718–721. Available at: https://doi.org/10.1038/s41586-022-05069-2.

**Acknowledgement:** This work was supported by the European Research Council (ERC) under the European Union's Horizon Europe research and innovation programme, Project No. 101141445 — ELEC_FROM_HEAT.

# POWER SUPPLY FOR ELECTROCALORIC COOLING DEVICE

**Christophe Baron[a,b], Elie Lefeuvre[b], Fabien Parrain[b], Martino Lo-Bue[a], Morgan Almanza[a]**

[a]Université Paris-Saclay, ENS Paris-Saclay, CNRS, SATIE, 91190, Gif-sur-Yvette, France, christophe.baron@ens-paris-saclay.fr

[b]Université Paris-Saclay, CNRS, C2N, 91190, Gif-sur-Yvette, France

## ABSTRACT

Compact, efficient, and reversible supplies are essential for electrocaloric cooling. Nanometer-thick electrodes give the opportunity to apply an electric field to small devices. Thus, the supply needs to be compact. The energy converted by the electrocaloric material represents less than 20% of the electrical energy that has been stored in the electrocaloric capacitance; the remaining part needs to be recovered during the discharge (Defay et al., 2018). To achieve high coefficients of performance, the power supply needs to be efficient and bidirectional. In this context, different topologies have been proposed: The bidirectional flyback (Thummala et al., 2015), the half-bridge (Mönch et al., 2023), and multilevel converters (Almanza et al., 2025). The flyback is based on a coupled inductor and is mostly developed for electroactive polymer. The half-bridge used an inductor to control the current and has been used with PMN electrocaloric ceramic. The multilevel converters are used for dielectric elastomer actuators. This work proposes to compare these topologies, using PVDF/ceramic-based electrocaloric materials.

**Keywords:** Half-bridge converter, Flyback converter, Multilevel converter, Power supply efficiency, electro-caloric materials

**References:**

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**Acknowledgement:** This work has been supported by France's national research agency on the ANR-20-CE05-0044, the ANR-23-CE05-0012, the ENS Paris-Saclay Phd scholarhip and the Graduate School Sciences de l'Ingénierie et des Systèmes of University Paris-Saclay.

# IMPLEMENTATION AND VALIDATION OF AN ACTIVE ELECTROCALORIC REGENERATOR COMPONENT IN TCC BUILDER

**Grega Belšak[(a)], Izak Oberčkal Pluško[(a)], Katja Vozel[(a)], Andrej Kitanovski[(a)], Markys Cain[(b)], Katja Klinar[(a)]**

[(a)] Faculty of Mechanical Engineering, University of Ljubljana Ljubljana, 1000, Slovenia, katja.klinar@fs.uni-lj.si

[(b)] Electrosciences Ltd, Farnham, GU9 9QT, UK

## ABSTRACT

In the scope of the THERMINATOR project an energy-harvesting prototype will be built, based on a combination of thermoelectric, thermoacoustic and electrocaloric devices (refrigerators, heat pumps and generators). Therefore, a fast and reliable approach is needed to evaluate the performance of a system where multiple different thermal devices, based on different thermal principles, are connected and work in unison. This will enable optimization to be carried out for all the possible combinations of connected devices for a desired combined output. Here we present a part of such framework, the active electrocaloric regenerator (AER) implemented as a component into an open-source code TCC Builder (Vozel et al., 2024). The code uses premeasured functions, which characterize the behavior of the device. These functions come from the experimental measurements or numerical simulations and can therefore include different effects, assumptions and simplifications. Taking an example of a prototype and its behavior describing functions from the literature, we verify the implementation of the component. Furthermore, we present a case study comparing various AER configurations and assessing their performance relative to that of individual AERs.

**Keywords:** active electrocaloric regenerator, optimization, TCC Builder, electrocaloric, heat transfer, refrigeration, heat pump

**References:**

Vozel, K., Klinar, K., Petelin, N. and Kitanovski, A., 2024. TCCbuilder: An open-source tool for the analysis of thermal switches, thermal diodes, thermal regulators, and thermal control circuits. *iScience*, 27(12), p.111263. Available at: https://doi.org/10.1016/j.isci.2024.111263

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# AGENTIC OPTIMISATION OF THERMAL CONVERSION SYSTEM: FRAMEWORK, ALGORITHMS AND INDUSTRIAL APPLICATIONS

**Abiodun Ayodeji[(a)], Ahmed Teyeb[(a)], Mohmmad Ali Asgar Abbas[(a)], Nagu Sathappan[(a)], Makis Livadas[(a)], Evelyne El Masri[(a)]**

[(a)]Brunel Innovation Centre, Brunel University London, Uxbridge UB8 3PH, UK,

abiodun.ayodeji@brunel.ac.uk

## ABSTRACT

Existing thermal conversion solvers, including TCCBuilder, allow multiple devices to be physically coupled by passing the output of one device to the input of the next. However, identifying optimal operating conditions for such chains still relies on brute-force, user-driven parameter selection within each device's allowable range. As the number of devices and control variables increases, this manual exploration becomes inefficient and limits the discovery of high-performance system architectures.

In this work, we introduce Agentic-TCCBuilder, which transforms TCCBuilder from a manual coupling tool into an autonomous design framework. By integrating multi-objective Bayesian optimization directly into the device-coupling workflow, the operating conditions of all devices are selected automatically and optimized jointly. This agent-driven approach treats the chained devices as a coupled system, enabling adaptive selection, learning and hierarchical planning. This results in a systematic discovery of high-performing thermal architectures while explicitly balancing competing objectives such as power output and efficiency.

Agentic-TTCBuilder is evaluated through a systematic comparative study of the thermoacoustic, electrocaloric and pyroelectric stack found in literature. Performance is assessed using key metrics including power output, power density, and conversion efficiency, allowing both absolute gains and trade-offs to be quantified. The preliminary results show that agent-optimized device chains consistently outperform their single-device and manually selected counterparts, achieving power output increases of 23% with improved efficiency. This gain demonstrates the innovation of Agentic-TCC as the framework for intelligent coupling and optimisation of thermal conversion system. Beyond the immediate applications in waste-heat recovery and precision temperature management, Agentic-TCCBuilder establishes a computational foundation for exploring emerging thermal conversion phenomena at the intersection of multiple technologies.

**Keywords:** Waste-heat recovery, Design Automation, Electrocaloric, Bayesian Optimisation, Thermoacoustic, Material discovery

# BULK CERAMICS AND AEROSOL-DEPOSITED FILMS FOR CALORIC APPLICATIONS

**Hana Uršič[a,b,*], Matteo d'Angelo[a], Victor Regis[a,b], Ivana Goričan[a,b]**

[a]Electronic Ceramics Department, Jožef Stefan Institute, Ljubljana, 1000, Slovenia.

[b]Jožef Stefan International Postgraduate School, Ljubljana, 1000, Slovenia.

*Presenting author: hana.ursic@ijs.si

## ABSTRACT

Many activities in solid-state cooling research focus on one of the caloric effects - electrocaloric (EC), magnetocaloric (MC), or mechanocaloric. Among these, the EC effect is triggered by voltage, which is readily available. In this contribution, we will discuss the $Pb(Sc_{0.5}Ta_{0.5})O_3$ and $Pb(Mg_{1/3}Nb_{2/3})O_3$-based ceramics and thick films for electrocaloric applications. The synthesized materials were used in various applications, such as caloric thick-film structures for flexible electronics. Further, we will discuss the preparation of caloric elements that exhibit both EC and MC effects, namely $Pb(Fe_{0.5}Nb_{0.5})O_3$–$BiFeO_3$ ceramics, as well as the multicaloric composite thick film based on the EC PMN–10PT and MC La-Fe-Si-based intermetallic alloy, where enhancement of electrocaloric performance can be observed. Finally, the lead-free alternatives will be discussed for EC applications.

**Keywords:** electrocaloric, multicaloric, ceramic, thick film

# INTERFACIAL ENGINEERING OF ELECTROCALORIC POLYMERS FOR HIGH STABILITY AND COOLING PERFORMANCE

**Donglin Han[a,b], Xiaoshi Qian[b], Shuhuai Yao[a]**

[a] The Hong Kong University of Science and Technology,
Hong Kong, 999077, China, medonglinh@ust.hk, meshyao@ust.hk

[b] Shanghai Jiao Tong University,
Shanghai, 200240, China, sjtuhandonglin@sjtu.edu.cn, xsqian@sjtu.edu.cn

## ABSTRACT

The widespread use of refrigeration devices has significant environmental impacts due to high energy consumption and carbon emissions. Electrocaloric (EC) refrigeration, offering high energy efficiency and zero direct carbon emissions, is a promising next-generation cooling technology. EC polymers are attractive for their flexibility and self-healing properties; however, large electric fields are typically required to achieve high entropy changes, often leading to undesirable dielectric breakdown. In this work, we developed interfacial modification strategies for the P(VDF-TrFE-CFE) terpolymer to enable long-time refrigeration with high cooling capacities. Introducing hierarchical organic interfaces combined with an annealing process yielded a breakdown field of 482 MV/m (Chen et al., 2025). Furthermore, incorporating organic-inorganic interfaces significantly enhanced the entropy change (Cai et al., 2025), achieving 55 J/kg·K under 80 MV/m, which is over twice that of the pristine terpolymer (23 J/kg·K). These results demonstrate an effective route to high-performance, stable EC polymer refrigeration.

**Keywords:** electrocaloric, ferroelectric polymers, interfaces, breakdown property, entropy change

**References:**

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CHEN, H., HAN, D., ZHAO, X., MAI, R., HUANG, C., LUO, R., ZHENG, S., LI, Q., ZHAO, Y., MA, Z., LIN, Y., ZHANG, F., YAO, T., CHEN, X., YANG, T., SHI, J., CHEN, J., DU, F. & QIAN, X. 2025. Tailoring Hierarchical Interfaces Enhances Dielectric and Electrocaloric Performance in Relaxor Ferroelectric Polymers. Advanced Fiber Materials, 7, 1290-1301. DOI: 10.1007/s42765-025-00564-3

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# NEW LEAD-FREE AURIVILLIUS OXIDES FOR ELECTROCALORIC COOLING: FROM BULK TO EPITAXIAL THIN FILMS

**Sara Lafuerza[(a), (b)], Javier Blasco, [(a), (b)], Marco Evangelisti[(a), (b)], David Gracia[(a), (b)], Gloria Subías, [(a), (b)], José Ángel Pardo[(a), (c)], Xavier Torrelles[(d)], Jessica Padilla-Pantoja[(e)], José Manuel Caicedo[(e)], José Santiso[(e)]**

[(a)]Instituto de Nanociencia y Materiales de Aragón (INMA), CSIC-Universidad de Zaragoza, Zaragoza, 50009, Spain

[(b)]Departamento de Física de la Materia Condensada, Universidad de Zaragoza, Zaragoza, 50009, Spain

[(c)]Departamento de Ciencia y Tecnología de Materiales y Fluidos, Universidad de Zaragoza, Zaragoza, 50009, Spain

[(d)]Institut de Ciència de Materials de Barcelona (ICMAB-CSIC) Bellaterra, 08193, Spain

[(e)]Catalan Institute of Nanoscience and Nanotechnology (ICN2) Bellaterra, 08193, Spain

## ABSTRACT

Aurivillius oxides are layered ferroelectrics with high dielectric strength, low leakage current, and excellent fatigue resistance, making them promising candidates for environmentally friendly solid-state electrocaloric (EC) cooling. Here, we present an investigation of lead-free $Sr_2Bi_4Ti_5O_{18}$ (SBTO5) compositions in both bulk ceramics and epitaxial thin films. Bulk samples synthesized by solid-state reaction and optimized via La and Nb codoping showed a tunable EC response, with a maximum adiabatic temperature variation ($\Delta T$) of about 0.3 K under 37 kV cm$^{-1}$ near 350 K, measured directly using a homemade quasi-adiabatic calorimeter (Lafuerza *et al.*, 2024). High-quality epitaxial SBTO5 thin films grown by pulsed laser deposition exhibited enhanced in-plane ferroelectricity and an improved $\Delta T$ compared to bulk codoped samples (Lafuerza *et al.*, 2025). These results pave the way for achieving a large EC response at room temperature in Aurivillius films through compositional and structural optimization, enabling scalable, efficient, and sustainable EC cooling.

**Keywords:** electrocaloric, lead-free ferroelectrics, Aurivillius oxides, epitaxial thin films

**References:**

Lafuerza, S. et al. (2024) 'Electrocaloric effect near room temperature in lead-free Aurivillius phase Sr2Bi4Ti5O18 upon La and Nb codoping', Journal of Alloys and Compounds, 983, p. 173923. doi: 10.1016/j.jallcom.2024.173923.

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**Acknowledgement:** This work was supported by the grants: Marie Skłodowska-Curie grant agreement No. 101029019 funded by the European Union's Horizon 2020 research and innovation program; CNS2023-144356 funded by MICIU/AEI/10.13039/501100011033 and European Union NextGenerationEU/PRTR; PID2021-124734OB-C21 and CEX2023-001286-S funded by MICIU/AEI/10.13039/501100011033, E11-23R & E12-23R funded by Diputación General de Aragón, and also 20256AT012 funded by CSIC.

# DIRECT THERMAL METHOD REVEALS HIGH EFFICIENCY OF ELECTROCALORIC LEAD-FREE $BA_{0,6}SR_{0,4}TIO_3$

**Julius Metzdorf**[(a)], **Patrick Corhan**[(a)], **Jan Schipper**[(a)], **Sakyo Hirose,** [(b)], **Kilian Bartholomé**[(a)]

[(a)]Fraunhofer IPM

[(b)]Murata Manufacturing Co., Ltd. Freiburg, 79110, Germany, julius.metzdorf@ipm.fraunhofer.de

## ABSTRACT

Electrocaloric cooling systems are dealt as a future environmentally friendly highly efficient alternative to vapor-compression. To fulfill that expectation the electrocaloric material does not only need sufficiently high adiabatic temperature change over a broad temperature range. It needs to be made from environmentally harmless constituents and has to show high efficiency. The efficiency of a material can be described by the figure of merit being the ratio of adiabatic temperature change to irreversible temperature change. Using a direct thermal method, only including a voltage source and an IR camera, we show that $(Ba_{0,6}Sr_{0,4})TiO_3$ multi-layer capacitor show a figure of merit of up to 10. This means that the upper efficiency limit for cascaded systems (without regeneration) built with this MLC could be up to 70% of the Carnot limit, thereby being one of the most efficient electrocaloric materials published so far.

**Keywords:** Electrocaloric, efficiency, thermal method, BaSrTiO3, Lead-free

**References:**

Schipper, J. *et al.* (2024) 'Introduction of novel method of cyclic self-heating for the experimental quantification of the efficiency of caloric materials shown for LaFe11,4Mn0,35Si1,26Hx,' *Journal of Physics Energy*, 6(3), p. 035006. https://doi.org/10.1088/2515-7655/ad5b89.

Unmüßig, S. *et al.* (2025) 'Direct thermal method to characterize the material efficiency of electrocaloric lead scandium tantalate multilayer ceramic capacitors,' *Materials*, 18(9), p. 1924. https://doi.org/10.3390/ma18091924

# LARGE LOW-FIELD-DRIVEN ELECTROCALORIC EFFECT IN MOLECULAR FERROELECTRICS

**Yuan Lin[a], Victorino Franco[b]*, Fengxia Hu[a]*, Baogen Shen[a]**

[a]Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences
Beijing, 100190, P. R. China, linyuan@iphy.ac.cn

[b] Dpto. Física de la Materia Condensada, ICMS-CSIC, Universidad de Sevilla, P.O. Box 1065 Sevilla, 41080, Spain

## ABSTRACT

Due to environmental-friendliness and high-efficiency, electrocaloric effect (ECE) is widely regarded as a refrigeration technology for tomorrow (Moya et al., 2020), (Klinar et al., 2024), (Neese et al., 2008), (Ma et al., 2017). Recent study focuses on two kinds of ferroelectrics: inorganic ceramics usually with low driving field but small entropy change (Nair et al., 2019), (Moya et al., 2013) and organic PVDF polymers with large entropy change but high driving field (Qian et al., 2021). Here, we bring up a new family, molecular ferroelectrics. For molecular ferroelectrics composed of organic and inorganic parts, they hold the potential to integrate the low driving field of inorganics and large entropy change of organics. We studied ECE in a series of molecular ferroelectrics. For TMCM-$CdCl_3$ which shows the largest low-field-driven ECE, the order-disorder transition of sphere-like organic cation $TMCM^+$ gives a large entropy change while the low-symmetry interaction provided by $CdCl_3$ inorganic chains accounts for the low driving field (Lin et al., 2025). Besides, I will briefly introduce our recent progress in full solid-state magnetic refrigeration devices (Lin et al., 2024).

**Keywords:** Electrocaloric, Organic-inorganic hybrids, Direct measurement, Meta-electric transition

**References:**

Klinar, K., Kitanovski, A. et al. (2024) ‘Perspectives and Energy Applications of Magnetocaloric, Pyromagnetic, Electrocaloric, and Pyroelectric Materials’, *Advanced Energy Materials*, 14(39), article 2401739.

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Moya, X. et al. (2013) ‘Giant Electrocaloric Strength in Single-Crystal BaTiO3’, *Advanced Materials*, 25(9), pp. 1360–1365.

Nair, B. et al. (2019) ‘Large electrocaloric effects in oxide multilayer capacitors over a wide temperature range’, *Nature*, 575(7783), pp. 468–472.

Neese, B. et al. (2008) ‘Large electrocaloric effect in ferroelectric polymers near room temperature’, *Science*, 321(5890), pp. 821–823.

Qian, X. et al. (2021) ‘High-entropy polymer produces a giant electrocaloric effect at low fields’, *Nature*, 600(7890), pp. 664–669.

## S12 Magnetocalorics & Thermomagnetics KOSOVEL HALL

Chair **Tino Gottschall** · Co-chair **Franca Albertini** · Help **Kamyar Dobakhti**

11:30 Shaping of thermomagnetic materials into heat exchangers — a process-level analysis
**Anja Waske** · *Bundesanstalt für Materialforschung und -prüfung*

11:42 Heusler alloys: a materials platform for exploring thermomagnetic energy harvesting
**Simone Fabbrici** · *IMEM-CNR*

11:54 High-performance thermomagnetic power generation materials and devices for low-grade waste heat harvesting
**Hu Zhang** · *University of Science and Technology Beijing*

12:06 Design and characterisation of rare-earth-free high-entropy alloys for thermomagnetic heat recovery
**Franca Albertini** · *IMEM-CNR*

12:18 Near net-shape manufacturing of LaFeSi-based regenerators towards commercialisation
**Hugo Vieyra** · *Vacuumschmelze GmbH & Co. KG*

12:30 Development and experimental testing of thermomagnetic motors
**Paulo Vinicius Trevizoli** · *Federal University of Minas Gerais*

12:42 Experimental comparison of thermomagnetic motor with different magnetic heat exchanger configurations
**Guilherme Hitoshi Kaneko** · *Meiji University*

12:54 Design particularities and first experimental results of a new generation thermomagnetic motor
**Jean Schneider** · *Magnoric*

13:06 A high-performance rotary thermomagnetic generator prototype for waste heat harvesting
**Francesco Cugini** · *University of Parma*

13:18 Finite element modeling and optimisation of a magnetic field source for thermomagnetic generation
**Radel Gimaev** · *FME, University of Ljubljana*

# SHAPING OF THERMOMAGNETIC MATERIALS INTO HEAT EXCHANGERS – A PROCESS LEVEL ANALYSIS

**Savvina M. Papaioannou[(a)], Kamyar Dobakhti[(b)], Suye Bu[(c)], Michael Maschek[(d)], Ekkes Brück[(c)], Andrej Kitanovski[(b)], Friderik Knez[(e)], Anja Waske[(a)]**

[(a)] Bundesanstalt für Materialforschung und -prüfung, Berlin, Germany, anja.waske@bam.de
[(b)] University Ljubljana, Ljubljana, Slovenia
[(c)] U Delft, Delft, The Netherlands
[(d)] Magneto B.V., Delft, The Netherlands
[(e)] Slovenian National Building and Civil Engineering Institute (ZAG), Ljubljana, Slovenia

## ABSTRACT

To date, there are very few technologies available for the conversion of low-temperature waste heat into electricity. Thermomagnetic generators are one approach proposed more than a century ago. Such devices are based on a cyclic change of magnetization with temperature, which is in practice often implemented by shaping a magnetic material into a heat exchanger with large surface to volume ratio. Within the EU MSCA initial training network Heat4Energy, thermomagnetic materials are shaped into heat exchangers which are then analysed in a prototype thermomagnetic generator for the conversion of low grade waste heat (<100°C) to electricity. In collaboration with the industrial stakeholders of the project, up-scalability and practical application issues of materials processing are addressed during the project. In this work, we analyse the environmental impacts and energy costs of key manufacturing stages at process level and give suggestions for the sustainable processing of these magnetic materials.

**Keywords:** thermomagnetic energy conversion, heat exchangers, environmental impacts, processing

**References:** https://heat4energy.eu/

# HEUSLER ALLOYS: A MATERIALS PLATFORM FOR EXPLORING THERMOMAGNETIC ENERGY HARESTING

**Simone Fabbrici[(a)], Lorenzo Gallo[(a,b)], Eleonora Rusconi[(a)], Francesco Cugini[(a,c)], Massimo Solzi[(a,c)], Franca Albertini[(a)]**

[(a)] IMEM - CNR, Parma, 43124, Italy. simone.fabbrici@cnr.it

[(b)] MISTER Smart Innovation, Bologna, 40129, Italy

[(c)] University of Parma, Parma, 43124, Italy

## ABSTRACT

Thermomagnetic energy harvesting is a promising technology for recovering the abundantly available low-grade waste heat. Performance relies on the development of improved magnetic materials that experience a magnetic or magnetostructural transition in a temperature range between ambient and 100 °C. Heusler compounds stand out as promising candidates due to their remarkable tunability of functional properties.

We will report on NiMnGa and NiMnIn based compounds (Cugini et al., 2025), properly doped with magnetic and non-magnetic elements to tune their first- and second-order transitions temperatures. Temperature and field dependent magnetization measurements will be used as an effective proxy (Fabbrici et al., 2022) to estimate the magnetic work attainable in thermomagnetic cycles between two thermal reservoirs with varying temperatures. We will discuss the effect of chemical substitution on the magnetic behavior of these materials, and their impact on thermomagnetic performance. Comparison with experimental results obtained in a laboratory scale prototype for notable compositions will be provided.

**Keywords:** Heusler compounds, martensitic transformation, thermomagnetic energy harvesting

**References:**

F. Cugini et al. (2025) In-operando test of tunable Heusler alloys for thermomagnetic harvesting of low-grade waste heat. Acta Mater. 288 120847 doi: 10.1016/j.actamat.2025.120847

S. Fabbrici et al. (2022) Magnetocaloric properties at the austenitic Curie transition in Cu and Fe substituted Ni-Mn-In Heusler compounds J. Alloy. Compd 899 163249 https://doi.org/10.1016/j.jallcom.2021.163249

**Acknowledgement**: This project has received funding from the European Union under grant agreement No 101119852.

# HIGH-PERFORMANCE THERMOMAGNETIC POWER GENERATION MATERIALS AND DEVICES FOR LOW-GRADE WASTE HEAT HARVESTING

**Haodong Chen[(a)], Mingze Liu[(a)], Shengyun Jin[(a)], Kaiming Qiao[(a)], Hu Zhang[(a, *)]**

[(a)] School of Materials Science and Engineering, University of Science and Technology Beijing. Beijing 100083, P R China, +86-10-62333733, zhanghu@ustb.edu.cn

## ABSTRACT

In recent years, thermomagnetic generator (TMG) has attracted much attention as a new technology for harvesting low-grade waste heat (Chen et al., 2025). However, the practical performance of most TMGs is still far below the theoretical value. We built an active TMG device for harvesting low-grade waste heat, and then evaluated the effect of different phase transitions on TMG performance. It is found that $Ni_2Mn_{1.4}In_{0.6}$ Heusler alloy with second-order phase transition exhibits large TMG performance, making it a good candidate for TMG materials (Chen et al., 2024). Then, we designed a novel TMG (Liu et al., 2023), in which the magnetocaloric material acts as a switch that controls the magnetic circuit. This design makes the magnetic flux in the induction coil change between the negative and positive maximum values, increasing the induced power by a factor of four. The optimized TMG performance is 2 to 3 orders of magnitude higher than those of other active TMGs.

**Keywords:** Thermomagnetic generation; Magnetocaloric effect; Waste heat harvesting.

**References:**

H. D. Chen, M. Z. Liu, and H. Zhang*. Enhanced heat transfer for thermomagnetic generation in low-grade waste heat harvesting. *Adv. Mater.* **37**, 2500544 (2025). https://doi.org/10.1002/adma.202500544

H. D. Chen, X. L. Liu, and H. Zhang*. Excellent thermomagnetic power generation for harvesting waste heat via a second-order ferromagnetic transition. *Mater. Horiz.* **11**, 2603 (2024). https://doi.org/10.1039/d3mh02225k

X. L. Liu, Z. H. Ma, and H. Zhang*. High-Performance Thermomagnetic Generator Controlled by a Magnetocaloric Switch. *Nat. Commun.* **14**, 4811 (2023). https://doi.org/10.1038/s41467-023-40634-x

# DESIGN AND CHARACTERIZATION OF RARE-EARTH-FREE HIGH ENTROPY ALLOYS FOR THERMOMAGNETIC HEAT RECOVERY

**Franca Albertini[(a)], Lorenzo Gallo[(a)], Simone Fabbrici[(a)], Giovanna Trevisi[(a)], Eleonora Rusconi[(a)], Francesco Cugini[(a,b)], Giovanni Garulli[(b)], Massimo Solzi[(a,b)], Pascal Boulet[(c)], Vincent Fournée[(c)]**

[(a)] Istituto IMEM-CNR, Parco Area delle Scienze 37/A, 43124, Parma, Italy, franca.albertini@cnr.it

[(b)] Dipartimento di Fisica, Università di Parma, Parco Area delle Scienze 7/A, 43124 Parma, Italy.

[(c)] Institut Jean Lamour, CNRS - Université de Lorraine, 2 allée André Guinier, 54011 Nancy, France.

## ABSTRACT

The development of thermomagnetic energy conversion technologies for low-grade heat recovery is critically dependent on the availability of materials with tailored properties. Key requirements include large magnetization changes at operational temperatures, high thermal diffusivity, and low specific and latent heat (D. Dzekan et al., 2021; F. Cugini et al., 2025).

In my talk I will discuss new findings on rare-earth-free high entropy alloys based on Fe-Ni-Ga-Mn-Si. Structural and magnetic characterizations reveal second-order Curie transitions near room temperature, which align well with the operational requirements of thermomagnetic devices. To assess their energy conversion potential, calculations based on experimental magnetization data were performed to estimate the magnetic work produced during ideal thermomagnetic cycles. These results show significant promise, with magnetic work values surpassing those of Gd when the hot source temperature exceeds 335 K. In-operando testing of these HEAs in a prototype thermomagnetic motor demonstrates that these alloys deliver high mechanical and electrical power outputs, outperforming values reported in the literature.

**Keywords:** Thermomagnetic heat recovery; High entropy alloys;

**References:**

Dzekan, D. et al. (2021) Efficient and affordable thermomagnetic materials for harvesting low grade waste heat. APL Mater, 9, 011105 doi: 10.1063/5.0033970.

F. Cugini et al. (2025) In-operando test of tunable Heusler alloys for thermomagnetic harvesting of low-grade waste heat. Acta Mater, 288, 120847, doi: 10.1016/j.actamat.2025.120847.

**Acknowledgement:** This project has received funding from the European Union under grant agreement No 101119852. This Project was partially funded by European Union – NextGenerationEU under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.1 - Call for tender No. 1409 of 14–09–2022 of Italian Ministry of University and Research (Project Code P2022KMXBL, Concession Decree No. 0001381 of 01/09/2023 adopted by the Italian Ministry of Universities and Research, CUP D53D23019360001, “Small-scale Thermomagnetic Energy harvesters: from materials to devices”).

# NEAR NET-SHAPE MANUFACTURING OF LAFESI-BASED REGENERATORS TOWARDS COMMERCIALIZATION

**Hugo Vieyra[a], Konrad Loewe[a], Matthias Katter[a]**

[a] Vacuumschmelze GmbH & Co. KG, Hanau, 63450, Germany, hugo.vieyra@vacuumschmelze.com

## ABSTRACT

LaFeSi-based alloys represent one of the few magnetocaloric material families with strong potential for large-scale implementation in magnetic refrigeration technology. Their good magnetocaloric properties, along with clear advantages in sustainability and cost effectiveness, further increase their chances of overthrowing benchmark gadolinium. Vacummschmelze is driving the introduction of LaFeSi-based alloys to the market tailored to the specific needs of its customers and partners.

The key challenge hindering widespread use of LaFeSi-alloys is the implementation of a shaping process that ensures reproducible, defect-poor geometries at production volumes exceeding laboratory scale. Although near net-shape manufacturing techniques are promising, only a limited number are suitable for process upscaling at competitive costs. In this work, we address this challenge by exploring a near net-shape manufacturing route for LaFeSi-based regenerators, aiming to combine geometric precision with mechanical integrity and scalability.

**Keywords:** LaFeSi, Neat-shaping, upscaling

# DEVELOPMENT AND EXPERIMENTAL TESTING OF THERMOMAGNETIC MOTORS

**P.V. Trevizoli[a,b], H.C.C. Michel[b,c], C.E.L. Silva[b], P.A.D. Chaves[b], M.S. Tadim[a], A.F.G. Pires[c], M.P.C. Bastos[c], D.L.B. Torres[a], T.T.M. Rocha[a,b], M.A. Câmara[a,b], C.M.P. Braga[c]**

[a]Department of Mechanical Engineering, Federal University of Minas Gerais (UFMG), Belo Horizonte, MG, 31270-901, Brazil, trevizoli@demec.ufmg.br

[b]Mechanical Engineering Graduate Program, Federal University of Minas Gerais (UFMG), Belo Horizonte, MG, 31270-901, Brazil

[c]Department of Electronic Engineering, Federal University of Minas Gerais (UFMG), Belo Horizonte, MG, 31270-901, Brazil

## ABSTRACT

Thermomagnetic motors are solid-state energy harvesters able to convert low-grade heat wastes (T<100ºC) into mechanical energy. The objective of this work is to present the key design parameters to successful thermomagnetic motor prototypes with different concepts: linear and rotary. It includes the relation between the magnetic field source, the fluid flow and heat transfer properties related to the MM heat exchanger towards the increasing of the produced power and operating frequency. Results showed that the linear apparatus was able to operate at 1.67Hz and produce powers of ~9W, using Gd spheres with 500µm; while the rotary motor presented maximum velocities around 350RPM and achieved maximum torques and powers of ~1.2Nm and ~4.5W, respectively, using Gd plates with 0.9mm thick. Both systems operated at 5ºC and 35-50ºC as heat sink and source temperatures. Considering the state-of-the-art, these results are among the highest values reported in the literature.

**Keywords:** Heat Waste Recovery, Energy Harvesting, Thermomagnetic Motors, Design, Mechanical Power

**References:**

Forman C et al (2016) 'Estimating the global waste heat potential'. Renew. Sust. Energ. Rev., 57: 1568–1579, doi: 10.1016/j.rser.2015.12.192.

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Rios H C et al (2024). 'Experimental evaluation of a linear thermomagnetic motor coupled to a spring mechanism'. In Proceedings of the 20th Brazilian Congress of Thermal Sciences and Engineering. ABCM.

Silva C E et al (2025). 'Novel rotary thermomagnetic motor with a fin rotor for energy harvesting: Initial results'. Energy Conversion and Management, 342: 120061, doi: 10.1016/j.enconman.2025.120061.

**Acknowledgement:** The authors are grateful for the financial support from Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) through Grant No. APQ-00735-23 (Demanda Universal); Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) through Grants No. 405970/2021-8 and No. 302269/2025-8; and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

# EXPERIMENTAL COMPARISON OF THERMOMAGNETIC MOTOR WITH DIFFERENT MAGNETIC HEAT EXCHANGER CONFIGURATIONS

**Guilherme Hitoshi Kaneko[(a)], Alisson Cocci de Souza[(b)], Tsuyoshi Kawanami[(a)]**

[(a)] Meij University, Kawasaki, Kanagawa, 214-8571, Japan, ghkaneko@gmail.com

[(b)]Federal Rural University of Pernambuco, Cabo de Santo Agostinho, PE, 54518-430, Brazil

## ABSTRACT

Thermomagnetic motors (TMMs) offer a promising approach for harvesting low-grade thermal energy by converting otherwise wasted heat into mechanical work through magnetization transitions near the Curie temperature. This study experimentally compares the output power of a purely magnetic TMM operating under different configurations. Two setups were tested: one with two magnetic heat exchangers (MHEs) and another with four MHEs, arranged either in series or in parallel. The serial configuration extends the stroke, while the parallel configuration enhances the magnetic force. Performance was evaluated under identical thermal and magnetic conditions. Results show that increasing the number of MHEs and optimizing their configuration significantly improves power generation. These findings advance the understanding of TMM behavior and support the development of more efficient systems for practical energy recovery applications.

**Keywords:** Thermomagnetic motor, Magnetic heat exchanger, Energy harvesting, Low-grade thermal energy.

# DESIGN PARTICULATITIES AND FIRST EXPERIMENTAL RESULTS OF A NEW GENERATION TERMOMAGNETIC MOTOR

**Jean Schneider, Michel Risser, Sergiu Lionte, Pierre Couturier, Simon Robert, Hugo du Moulinet d'Hardemare**

[(a)] Magnoric SAS, Duppigheim, 67120, France, sergiu.lionte@magnoric.com

## ABSTRACT

A significant part of the low-grade waste heat is massively under-exploited and typically released into the environment without recovery. The main reason lies in lack of efficient solution available on large scale for low temperature sources. A proper solution could be the thermomagnetic energy conversion via the magnetocaloric effect, which can easily be applied to low temperature sources.

In this paper we present the design and the first experimental results of a next generation thermomagnetic motor based on an axial architecture. The magnetic field profile and the inside thermal leakages presented as well as the initial performance results. The output mechanical power is investigated for a controlled frequency, and the numerically simulation is experimentally validated. The initial results show that the TMM could easily be used for heat harvesting at low temperature level.

**Keywords:** Thermomagnetic motor, waste heat harvesting, magnetocaloric effect

**References:** Risser, M., Lionte, S., Marrazzo, F., Till, Z., Muller, C. (2024), Numerical and experimental study of a reversible thermomagnetic motor, 10th IIR International Conference on Caloric Cooling and Applications of Caloric Materials, Baotou, China. DOI: 10.18462/iir.thermag.2024.0007

**Acknowledgement:** This work has been partially financed by France 2030 future innovation program (*Innovation d'Avenir*) of the Grand Est region and the BPI of France

# A HIGH-PERFROMANCE ROTARY THERMOMAGNETIC GENERATOR PROTOTYPE FOR WASTE HEAT HARVESTING

**Francesco Cugini[a,b], Giovanni Garulli[a], Lorenzo Gallo[b], Luca Cattani[c], Fabio Bozzoli[d], Simone Fabbrici[b], Franca Albertini[b], Massimo Solzi[a,b]**

[a] Department of Mathematical, Physical and Computer Sciences, University of Parma, Parco Area delle Scienze 7/A, 43124 Parma, Italy. francesco.cugini@unipr.it

[b] IMEM-CNR Institute, Parco Area delle Scienze 37/A, 43124 Parma, Italy

[c] Department of Engineering for Industrial Systems and Technologies, Parco Area delle Scienze 181/A, 43124 Parma, Italy

[d] Department of Industrial Engineering, University of Firenze, Via di S. Marta, 3, 50139 Firenze, Italy

## ABSTRACT

In this work, we present a laboratory-scale prototype of a rotary thermomagnetic generator, developed to enable rapid assessment of thermomagnetic materials and to serve as a versatile test-bench for device architecture optimization (Cugini, 2025). The system operates according to the Curie wheel principle, employing a thin rotor, made of a thermomagnetic material, that is exposed to a magnetic field gradient and exchanges heat with two thermal reservoirs. A custom-designed electric generator enables simultaneous measurement of torque, rotational speed, mechanical and electrical power output. The effective temperature gradient during operation is monitored using a high-sensitivity infrared camera. The prototype was tested with several classes of promising thermomagnetic materials, integrated with a straightforward rotor fabrication method assisted by 3D-printing. When operated with optimized NiMnIn Heusler alloys and MnFePSi compounds, the generator exhibited mass power density and efficiency values that surpass those of previously developed generators operating within the 30–60 °C temperature range.

**Keywords:** thermomagnetic generator, heat harvesting, Heusler alloys, MnFePSi compounds

**References:** F. Cugini et al., (2025) In-operando test of tunable Heusler alloys for thermomagnetic harvesting of low-grade waste heat*, Acta Mater.*, 288, 120847. https://doi.org/10.1016/j.actamat.2025.120847

**Acknowledgement:** This work received financial support from European Union -NextGenerationEU (PRIN 2022 PNRR Project “STEve” P2022KMXBL, CUP: D53D23019360001).

# FINITE ELEMENT MODELING AND OPTIMIZATION OF A MAGNETIC FIELD SOURCE FOR THERMOMAGNETIC GENERATION

**Radel Gimaev[(a)], Katja Klinar[(a)], Andrej Kitanovski[(a)]**

[(a)] University of Ljubljana, Faculty of Mechanical Engineering,
Aškerčeva 6, 1000 Ljubljana, Slovenia, andrej.kitanovski@fs.uni-lj.si

## ABSTRACT

Low-grade waste heat is of great interest for energy recovery, as it accounts for up to 65% of total heat losses, while only 6% is currently utilized (Langan and O'Toole, 2017). One technology for waste heat harvesting is the active thermomagnetic generator (TMG).

The performance and cost of a TMG are influenced by the field source characteristics. In permanent magnet-based systems the magnetic configuration determines the magnetic flux distribution, consequently impacting TMG efficiency. As the magnetic field source is one of the costliest TMG components, minimizing its size and material usage is a critical task, often performed using finite element modeling.

This study investigates the influence of the magnetic field source on TMG performance. TMG operation was simulated using Ansys Maxwell to evaluate output characteristics depending on field source parameters. Based on the parametric analysis, the field source proposed by (Tomc et al., 2023) was optimized for use in TMGs.

**Keywords:** thermomagnetic, low-grade waste heat, magnetic field source, finite element modeling

**References:**

Langan, M. and O'Toole, K. (2017). A new technology for cost effective low grade waste heat recovery. Energy Procedia, 123, pp.188–195. doi:https://doi.org/10.1016/j.egypro.2017.07.261.

Tomc, U., Nosan, S., Klinar, K. and Kitanovski, A. (2023). Towards powerful magnetocaloric devices with static electro-permanent magnets. Journal of advanced research, [online] 45, pp.157–181. doi:https://doi.org/10.1016/j.jare.2022.05.001.

## S13 Magnetocalorics & Thermomagnetics LINHART HALL

Chair **Victorino Franco** · Co-chair **Simone Fabbrici** · Help **Jorge Revuelta Losada**

14:30 Magnetocaloric and barocaloric materials
**Yuan Lin** · *Beijing National Lab. for Condensed Matter Physics, IoP, CAS*

14:42 Theoretical analysis on magnetocaloric properties of $Nd_{1-x}Pr_xAl_2$ series compounds
**Paula Ribeiro** · *Rio de Janeiro State University*

14:54 A high-throughput study of compositionally graded LaFeSi-based films
**André Beleza** · *Institut Néel, CNRS*

15:06 Design of Halbach cylinders: a cost evaluation framework
**Eduardo Felipe Neves** · *UFMG*

15:18 Ab initio understanding of large caloric effects and minimal hysteresis in first-order magnetic transitions
**Eduardo Mendive Tapia** · *University of Barcelona*

15:30 A spring-assisted linear thermomagnetic conversion system: experimental results
**Paulo Vinicius Trevizoli** · *Federal University of Minas Gerais*

15:42 Research on the cycle performance of cascade room-temperature magnetic heat pump system
**Xiaoliang Yuan** · *South China University of Technology*

15:54 New minimalism-style magnetic heat pumps: fusion reconstruction of magnetocaloric effect and loop heat pipe
**Fucheng Chen** · *South China University of Technology*

16:06 Evaluation of Curie temperature effects in the performance of active magnetic regenerators — Part I: second-order phase transition
**Urban Tomc** · *FME, University of Ljubljana*

Evaluation of Curie temperature effects in the performance of active magnetic regenerators — Part II: first-order phase transition
**Guilherme Fidelis Peixer** · *POLO — UFSC*

# GIANT CRYOGENIC MAGNETOCALORIC EFFECT IN $EUCL_2$

**Fengxia Hu, Yuan Lin, Baogen Shen**
*Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences,*
Beijing, 100190, P. R. China. *fxhu@iphy.ac.cn*

## ABSTRACT

Cryogenic magnetocaloric materials attract growing attention for solid-state refrigeration technologies, especially in sub-Kelvin applications. We discovered giant cryogenic magnetocaloric effect in orthorhombic EuCl2, (Wang et al., 2024) where a ferromagnetic ground state with excellent single-ion behavior of Eu2+ and free spins has been demonstrated by combining ab initio calculations with Brillouin function analysis and magnetic measurements. At a low field of 1 T, EuCl2 achieves the highest-ever record of $-\Delta$ SM~36.8 J · kg−1 · K−1. Direct adiabatic demagnetization measurements demonstrated that the large −ΔSM allows EuCl2 to maintain a long holding time at sub-Kelvin temperature (~346 mK), surpassing prior reported materials. We'll also briefly introduce our recent work on device and barocaloric/electrocaloric effect (Lin et al., 2024, 2025),(Gao et al., 2024), particularly, low pressure reversibly driving colossal barocaloric effect has been achieved in two-dimensional van-der-Waals alkylammonium halides (Gao et al., 2024).

**Keywords:** cryogenic magnetocaloric effect, barocaloric effect

**References:**

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# THEORETICAL ANALYSIS ON MAGNETOCALORIC PROPERTIES OF $ND_{1-X}PR_XAL_2$ SERIES COMPOUNDS

**Paula de O. Ribeiro[(a)*], Bruno de P. Alho[(a)], Rodrigo S. de Oliveira[(a)], Pedro J. von Ranke[(a)], Sérgio S. dos Santos Jr.[(a)], Eduardo P. Nobrega[(a)], Vinícius S. R. de Sousa[(a)], Alexandre M. G. Carvalho[(a)]**

[(a)] Instituto de Física Armando Dias Tavares, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, 20550-013, Brazil, paula.ribeiro@gmail.com

## ABSTRACT

One promising application of magnetocaloric effect is hydrogen liquefaction, a process that requires cooling hydrogen gas below 20 K to achieve the liquid phase, which could significantly improve energy efficiency and sustainability in hydrogen storage and transport technologies (Tang et al., 2022).

Liu et. al (Liu et al., 2023)reported experimental results on $Nd_{1-x}Pr_xAl_2$ series compounds, where it was mentioned that $PrAl_2$ and $Pr_{0.75}Nd_{0.25}Al_2$ show maximum $\Delta S_T$ larger than (or comparative to) other heavy rare-earth Laves phases (Liu et al., 2022).

In this work we present a theoretical investigation of the magnetothemal and magnetocaloric effect in the intermetallic series compounds $Nd_{1-x}Pr_xAl_2$. Our model Hamiltonian includes the crystalline electrical field, exchange, and Zeeman interactions in both $Nd^{3+}$ and $Pr^{3+}$ sublattices. A reasonable agreement was achieved between the theory and experimental data concerning heat capacity, $\Delta S_T$ and $\Delta T_{ad}$ (magnetocaloric quantities).

Additionally, the analysis of magnetic anisotropy and simulations for the rotating magnetocaloric effect were performed.

**Keywords:** magnetocaloric, mean field, crystalline electrical field, rare-earth, magnetic anisotropy.

**References:**

Liu, W. et al. (2022) 'A study on rare-earth Laves phases for magnetocaloric liquefaction of hydrogen', Applied Materials Today, 29, article 101624. doi: 10.1016/j.apmt.2022.101624.

Liu, W. et al. (2023) 'Designing magnetocaloric materials for hydrogen liquefaction with light rare-earth Laves phases', Journal of Physics: Energy, 5, pp. 034001. doi: 10.1088/2515-7655/accb0b.

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**Acknowledgement:** Rio de Janeiro State University acknowledges financial support from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001, CNPq – Conselho Nacional de Desenvolvimento Científico e Tecnológico – Brazil and FAPERJ - Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro.

# A HIGH THROUGHPUT STUDY OF COMPOSITIONALLY GRADED LAFESI-BASED FILMS

**André Beleza*, Tchilabalo Pakam, William Rigaut, Pierre Le Berre, Lukas Fink, Richard Haettel, Thibaut Devillers, Nora Dempsey**

Univ. Grenoble Alpes, CNRS, Institut Néel, 38000 Grenoble, France

* andre.beleza@neel.cnrs.fr

## ABSTRACT

The magnetic properties of $La(Fe,Si)_{13}$-based alloys, including Curie temperature ($T_C$), magnetization, and magnetocaloric effect, can be tuned via composition (Shen et al., 2009), (Niitsu et al., 2013). We used the combinatorial thin-film approach (Green et al., 2013) to study the effect of element substitution and processing conditions on the structural and magnetic properties of $La(Fe,Si)_{13}$ and $La(Fe,Si,X)_{13}$ (X = Co, Mn …) films. Compositionally graded films were deposited by triode sputtering onto stationary thermally oxidized 100 mm Si substrates. High-throughput characterization across full wafers was performed using EDX spectroscopy, profilometry, SEM, XRD, and MOKE magnetometry, with selected samples analyzed by SQUID-VSM. EDX composition maps and a pseudo-ternary diagram of $T_C$ for a La-Fe-Si-Co library deposited at 700°C were created. The highest $T_C$ of 304 K occurred in the Co-rich region, and correlations between elemental distribution, structure, and magnetic properties are discussed.

**Keywords:** Combinatorial Study, High-throughput characterization, Thermomagnetic Materials

**References:**

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**Acknowledgement:** This project has received funding from the European Union under grant agreements 101119852 (Heat4Energy) and 101161135 (MAGCCINE).

# DESIGN OF HALBACH CYLINDERS: A COST EVALUATION FRAMEWORK

**E.F. Neves[a,d], H.C.C. Michel[b,c], T.T.M. Rocha[a,b], M.A. Câmara[a,b], C.M.P. Braga[c], A. L. P. de Faria[d], P.V. Trevizoli[a,b]**

[a]Mechanical Engineering Graduate Program, Federal University of Minas Gerais (UFMG), Belo Horizonte, MG, 31270-901, Brazil

[b]Department of Mechanical Engineering, Federal University of Minas Gerais (UFMG), Belo Horizonte, MG, 31270-901, Brazil, trevizoli@demec.ufmg.br

[c]Department of Electronic Engineering, Federal University of Minas Gerais (UFMG), Belo Horizonte, MG, 31270-901, Brazil

[d]CIT Senai ITR, Lagoa Santa, MG 33233-569, Brazil apfaria@fiemg.com.br

## ABSTRACT

The Halbach cylinder is a commonly used permanent magnet configuration with applications ranging from medical devices to industrial equipment, including thermomagnetic conversion systems such as Active Magnetic Regenerators and Thermomagnetic Motors. These applications often demand either static or variable magnetic fields with high intensity across large gaps. Therefore, key design considerations include magnetic field strength and volume, as well as magnet material usage and associated costs. In partnership with CIT SENAI-ITR, a NdFeB magnet manufacturer, this work has the objective of evaluating Halbach cylinder designs through a cost-optimization approach. A simplified, validated mathematical model is employed to analyze various geometries. Each configuration is assessed not only for magnetic field metrics but also in terms of material cost, based on real market pricing. The proposed approach may support the development of efficient and economically viable Halbach configurations for practical applications.

**Keywords:** NdFeB, Permanent Magnets, Halbach Cylinders, Design, Cost Evaluation

**References:**

R. Bjørk *et al* (2010). 'Review and comparison of magnet designs for magnetic refrigeration'. *Int. J. Refrig*. 33: 437–448, doi: 10.1016/j.ijrefrig.2009.12.012.

J.M.D. Coey (2002). 'Permanent magnet applications'. *J. Magn. Magn. Mater.,* 248: 441–456, doi: 10.1016/S0304-8853(02)00335-9.

P.V. Trevizoli *et al* (2015). 'Design of nested Halbach cylinder arrays for magnetic refrigeration applications'. *J. Magn. Magn. Mater.,* 395: 109-122, doi: 10.1016/j.jmmm.2015.07.023.

**Acknowledgement:** The authors are grateful for the financial support from Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) through Grant No. APQ-00735-23 (Demanda Universal); Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) through Grants No. 405970/2021-8 and No. 302269/2025-8; Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001. Serviço Nacional de Aprendizagem (SENAI) and Federação da Indústria do Estado de Minas Gerais (FIEMG).

# AB INITIO UNDERSTANDING OF LARGE CALORIC EFFECTS AND MINIMAL HYSTERESIS IN FIRST-ORDER MAGNETIC TRANSITIONS

**Eduardo Mendive Tapia[(a)], Wei Liu[(b)], David Boldrin[(c)], Konstantin Skokov[(b)], Oliver Gutfleisch[(b)]**

[(a)] Departament de Física de la Matèria Condensada, Facultat de Física, Universitat de Barcelona Barcelona, 08028, Catalonia, Spain, e.mendive.tapia@ub.edu

[(b)] Institute of Materials Science, Technical University of Darmstadt, 64287 Darmstadt, Germany, wei.liu@tu-darmstadt.de

[(c)] School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, United Kingdom, david.boldrin@glasgow.ac.uk

## ABSTRACT

Caloric effects in magnetic materials are particularly pronounced near first-order magnetic phase transitions (Pecharsky et al., 1997). However, these transitions often exhibit detrimental thermal hysteresis. While magnetovolume coupling is a well-established driver of first-order behavior (Bean et al., 1962), the role of purely electronic mechanisms, as well as the connection of these two mechanisms to thermal hysteresis, remains not fully understood. In this work, we employ the disordered local moment (DLM) framework within density functional theory (DFT) (Gyorffy et al., 1985), (Mendive-Tapia et al., 2020a, 2022) and carry out experiments to investigate the temperature-dependent magnetic and caloric properties of materials exhibiting different types of magnetic phase transitions. We present new results quantifying how electronic and magnetovolume interactions induce first-order transitions in rare-earth-based materials. By integrating these findings with previous theoretical predictions and experimental observations (Abadia-Huguet et al., 2025), (Mendive-Tapia et al., 2020a, 2020b, 2023), (Liu et al., 2022, 2024), we identify the microscopic factors that underpin a unified view of first-order behavior and its associated thermal hysteresis across a broad range of published experimental data. These insights provide design principles for engineering magnetic materials that combine large caloric responses with minimal hysteresis.

**Keywords:** Magnetic materials, ab initio thermodynamics, first-order transitions, hysteresis

**References:** Abadia-Huguet, A., Mendive-Tapia, E. et al. (2025) Applied Materials Today, 44, article 102749.

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Pecharsky, V.K. and Gschneidner, K.A. (1997) Physical Review Letters, 78, p. 4494.

**Acknowledgement:** We acknowledge financial support from MICIU/AEI/10.13039/501100011033/ and FEDER, UE with Grant. No. PID2024-161052NA-I00, the Clean Hydrogen Partnership within the framework of the HyLICAL project (Grant No. 101101461), and the Deutsche Forschungsgemeinschaft (DFG) within the CRC/TRR 270 (Project-ID 405553726). We are also grateful to the Computational Materials Design Department at MPI-SusMat for the provision of computing time on their HPC cluster.

# A SPRING-ASSISTED LINEAR THERMOMAGNETIC CONVERSION SYSTEM: EXPERIMENTAL RESULTS

**M.P.C. Bastos[c], H.C.C. Michel[b,c], T.T.M. Rocha[a,b], M.A. Câmara[a,b], C.M.P. Braga[c], A. Rowe[d], P.V. Trevizoli[a,b]**

[a]Department of Mechanical Engineering, Federal University of Minas Gerais (UFMG), Belo Horizonte, MG, 31270-901, Brazil, trevizoli@demec.ufmg.br

[b]Mechanical Engineering Graduate Program, Federal University of Minas Gerais (UFMG), Belo Horizonte, MG, 31270-901, Brazil

[c]Department of Electronic Engineering, Federal University of Minas Gerais (UFMG), Belo Horizonte, MG, 31270-901, Brazil

[d]Institute for Integrated Energy Systems (IESVic), University of Victoria, Victoria, BC, V8W2Y2, Canada

## ABSTRACT

The growing demand for energy requires efficient conversion solutions. Thermomagnetic motors are solid-state energy harvesters able to convert low-grade heat wastes into mechanical energy, potentially increasing systems efficiency. This work presents advances on the previous version of a linear thermomagnetic system prototype assisted by a spring mechanism. The experimental setup features a Halbach magnetic circuit, with a maximum magnetic field of 1.35 T. A 54 g packed bed of Gd spheres with 0.5 mm diameter is used as thermomagnetic material. The linear motion, driven by the interaction between magnetic and elastic forces, converts thermal energy into mechanical work. Novel experimental results reached maximum output powers of 5.83 W, 9.04 W and 9.09 W, respectively, at the heat source temperature of 35ºC, 40ºC and 45ºC, while the heat sink is at 5ºC. The maximum frequency is 1.67 Hz. These results offering promising insights for potential application in heat recovery systems.

**Keywords:** Heat Waste Recovery, Energy Harvesting, Thermomagnetic Motors, Linear, Prototype.

**References:**

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# RESEARCH ON THE CYCLE PERFORMANCE OF CASCADE ROOM-TEMPERATURE MAGNETIC HEAT PUMP SYSTEM

**Xiaoliang Yuan[(a)], Jianghong Wu[(a*)], Haoxian Yu[(b)]， Fucheng Chen[(a)]**

[(a)] School of Mechanical and Automotive Engineering, South China University of Technology Guangzhou, 510640, China, pmjhwu@scut.edu.cn

[(b)] Shenzhen SiCarrier Technologies Co., Ltd., Shenzhen, 518116, China

## ABSTRACT

Traditional heat pump technology is facing challenges due to the issue of refrigerant substitution, while magnetic heat pump technology has attracted attention due to its environmental friendliness and energy-saving potential. To increase its temperature span and wide-temperature heating capacity, a cascade room-temperature magnetic heat pump system was proposed. A hybrid cycle is adopted, combining the Brayton and Ericsson cycle, and the proportions of these two cycles in the new cycle are adjusted through mixing coefficient. The intermediate water tank is used to replace the inter-stage heat exchanger to reduce the heat exchange temperature difference between stages. The maximum temperature span reached 32 K, which was 2.6% higher than that of the Brayton cycle. Compared with the single-stage system temperature span, it has increased by 61.6%. The hot end temperature has reached 42.3 °C, which is currently the highest hot end temperature obtained under the same magnetic field intensity system known.

**Keywords:** Magnetic heat pump; Active magnetic regenerator; Hybrid cycle; Temperature span; Cascade cycle

**Acknowledgement:** This work was supported by the Key R&D Program of Shandong Province, China, No.2023CXGC010301 and National Natural Science Foundation of China [Grant No. 52276008].

# NEW MINIMALISM STYLE MAGNETIC HEAT PUMPS: FUSION RECONSTRUCTION OF MAGNETOCALORIC EFFECT AND LOOP HEAT PIPE

**Fucheng Chen[a], Jianghong Wu[a*], Geyao Xu[a], Yaokang Zhang[b], Hangye Zhang[c], Yong Li[a]**

[a] School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou, 510640, China, pmjhwu@scut.edu.cn

[b] College of Ocean Engineering and Energy, Guangdong Ocean University, Zhanjiang, 524088, China

[c] Institute of Process Equipment, College of Energy Engineering, Zhejiang University, Hangzhou, Zhejiang, 310027, China

## ABSTRACT

The development of room temperature magnetic heat pumps is hindered by the trade-off between operating frequency and heat exchange efficiency. Here we introduce a new minimalism magnetic heat pump: magnetocaloric loop heat pipe that couples phase change heat transfer with the magnetocaloric effect. A compact multi-stage prototype (circumferential radius 100 mm, inner radius 6 mm) shows interlayer thermal resistance of $1e^{-3}$ K $W^{-1}$, a 99.98% reduction compared to solid-state conduction. A three-stage cascade prototype achieved a 6 K no-load temperature span, while modeling predicts up to 20 K for ten-stage. The one-stage prototype was able to achieve a maximum specific heating power of 7 W $g^{-1}$ at a cycle frequency of 10 Hz. This novel cycle features the advantages of rapid heat regeneration and ultralow thermal resistance, enabling cooling and heating in confined spaces and highlighting phase-change heat transfer as a promising route for future caloric heat pumps.

**Keywords:** Magnetic heat pump; Magnetocaloric loop heat pipe; Cascade thermodynamic cycle; Phase change heat transfer; Minimalism compact prototype

**Acknowledgement:** This research was funded by the National Natural Science Foundation of China (Grant no. 52276008) and the Key R&D Program of Shandong Province, China, No.2023CXGC010301.

# EVALUATION OF CURIE TEMPERATURE EFFECTS IN THE PERFORMANCE OF ACTIVE MAGNETIC REGENERATORS - PART I: SECOND ORDER PHASE TRANSITION

**Urban Tomc[(a)], Guilherme F. Peixer[(b)], Chistian R. H. Bahl[(c)], Kaspar K. Nielsen[(c)], Jaime A. Lozano[(b)], Jader R. Barbosa Jr.[(b,d)], Andrej Kitanovski[(a*)]**

[(b)]University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva 6, 1000 Ljubljana, Slovenia,

*Corresponding author, email: andrej.kitanovski@fs.uni-lj.si

[(b)] POLO - Research Laboratories for Emerging Technologies in Cooling and Thermophysics, Department of Mechanical Engineering, Federal University of Santa Catarina (UFSC), Florianópolis, SC, 88040-900, Brazil

[(c)] Department of Energy Conversion and Storage, Technical University of Denmark, Anker Engelunds Vej, 2800 Kgs, Lyngby, Denmark

[(d)] Craft & Hawkins Department of Petroleum Engineering, Louisiana State University, Baton Rouge, LA 70803, United States.

## ABSTRACT

Magnetic refrigeration is a promising alternative to conventional cooling systems, offering higher efficiency and environmental benefits. This study addresses a critical but underexplored issue: the impact of Curie temperature ($T_C$) uncertainty in multilayer active magnetic regenerators (AMRs). Although multilayer AMRs extend the operational temperature range by combining materials with different $T_C$, their performance is sensitive to $T_C$ variations due to manufacturing tolerances. A numerical model based on La-Fe-Co-Si materials was developed and combined with machine learning to evaluate the effects of statistical $T_C$ deviations. Monte Carlo simulations using neural networks showed that even small deviations ($\sigma > 1$ K) can significantly reduce the probability of reaching the desired cooling power, especially in systems with many layers. The study highlights the importance of precise material control and presents a novel methodology for uncertainty assessment using AI tools, supporting the development of reliable and commercially viable magnetocaloric cooling technologies.

**Keywords:** Uncertainty Analysis, Monte Carlo method, Artificial Neural Networks, Numerical Model, Magnetocaloric, Active Magnetic Regenerator

**References:** U. Tomc, G. F. Peixer, C. R. H. Bahl, et al. (2025). Influence of Layering and Curie Temperature Uncertainty on the Performance of Multilayer Active Magnetic Regenerators. Advanced Functional Materials, e24282. https://doi.org/10.1002/adfm.202424282

# EVALUATION OF CURIE TEMPERATURE EFFECTS IN THE PERFORMANCE OF ACTIVE MAGNETIC REGENERATORS - PART II: FIRST ORDER PHASE TRANSITION

**Guilherme F. Peixer[(a)], Urban Tomc[(b)], Andrej Kitanovski[(b)], Jader R. Barbosa Jr.[(a,c)], Jaime A. Lozano[(a)]**

[(a)] POLO - Research Laboratories for Emerging Technologies in Cooling and Thermophysics, Department of Mechanical Engineering, Federal University of Santa Catarina (UFSC), Florianópolis, SC, 88040-900, Brazil,

guilherme.peixer@polo.ufsc.br

[(b)]University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva 6, 1000 Ljubljana, Slovenia.

[(c)]Craft & Hawkins Department of Petroleum Engineering, Louisiana State University, Baton Rouge, LA 70803, United States.

## ABSTRACT

Vapor-compression cooling systems are energy-intensive and environmentally harmful, motivating the search for cleaner and more efficient alternatives. Magnetic refrigeration has emerged as a promising solution, but its technological maturity is limited by several factors, including variations in the Curie temperature of magnetocaloric alloys. In this study, a Monte Carlo uncertainty analysis was conducted using Artificial Neural Networks trained on experimentally validated numerical data to quantify the effects of Curie temperature variability. The results reveal that current material uncertainties lead to significant performance uncertainty, forcing designers to oversize prototypes by 30–80% to ensure stable operation. This oversizing increases system cost and complexity, while large-scale manufacturing remains hindered by insufficient quality control of magnetocaloric materials. Improving material uniformity is therefore critical for advancing magnetic refrigeration toward practical applications.

**Keywords:** Uncertainty Analysis, Monte Carlo method, Artificial Neural Networks

**Acknowledgement:** Erasmus+ Programme

## S14 Mechanocalorics & Thermomechanics KOSOVEL HALL

Chair **Xavier Moya** · Co-chair **Gaël Sebald** · Help **Jure Zupančič**

14:30 Numerical modelling of a cascaded barocaloric cooler
**Àlvar Torelló** · *Universitat Politècnica de Catalunya*

14:42 Numerical analysis on the optimisation of a heat recovery cycle for an elastocaloric device
**Lucrezia Verneau** · *Univ. degli Studi di Napoli Federico II*

14:54 Influence of loading and unloading profiles on an active elastocaloric regenerator: a numerical study
**Vincenzo Orabona** · *Univ. degli Studi di Napoli "Federico II"*

15:06 SMArtCool — modelling and simulation of elastocaloric material behaviour for translatory cooling concepts
**Felix Welsch** · *ZeMA gGmbH*

15:18 Elastocaloric measurement apparatus for elastomers with bimodal (extension / compression) strain-rate and temperature control
**Kenneth Roy Rojo** · *INMA, CSIC — Universidad de Zaragoza*

15:30 Thermo-mechano-caloric investigation of cyclic training effects in NiTi-based elastocaloric materials
**Franziska Louia** · *Saarland University*

15:42 Pressure-induced measurements of barocaloric effect
**Tomaž Pšeničnik** · *FME, University of Ljubljana*

15:54 P–T structural characterisation of spin-crossover compound $Fe(pyrazine)[Fe(CN)_5(NO)]$
**Maxime Deutsch** · *CRM2, Lorraine University*

16:06 Giant mechanocaloric effects in confined spin-crossover compounds under uniaxial loading: transferable design rules
**Enric Stern-Taulats** · *University of Barcelona*

16:18 Colossal barocaloric effects in spin-crossover compounds with a sharp spin transition
**Adrià Gràcia Condal** · *Universitat Politècnica de Catalunya*

# NUMERICAL MODELING OF A CASCADED BAROCALORIC COOLER

**Àlvar Torelló[(a)], Josep-Lluís Tamarit[(a)], Pol Lloveras[(a)]**

[(a)] Group of Characterization of Materials, Department of Physics and Barcelona Research Center in Multiscale Science and Engineering, Universitat Politècnica de Catalunya, Barcelona, 08019, Spain, alvar.torello@upc.edu,
+34 93413 40 77

## ABSTRACT

Barocaloric materials have stirred strong interest in recent years due to the colossal effects reported in several material families (Lloveras et al., 2021). Yet, the development of subsequent cooling devices and prototypes remains in its early research stages. Here, we present a novel barocaloric cooler design based on the principle of cascading and thermal switches (Torello et al., 2025). The design utilizes a prototypical colossal barocaloric material and takes into account relevant features previously overlooked, such as its colossal latent heat, the time it takes to apply pressure, and the high- pressure cell thickness. Our results show that a second law efficiency of 23% is achievable for a temperature span of 15 K and a cooling power of 1.5 kW $kg^{-1}$ of refrigerant. We will also provide insights in work recovery and strategies on how to optimize it.

**Keywords:** Barocaloric cooling, finite element, multistage, second law efficiency.

**References:**

Lloveras, P. and Tamarit, J.L. (2021) 'Advances and obstacles in pressure-driven solid-state cooling: A review of barocaloric materials', MRS Energy & Sustainability, 8, pp. 3–15.

Torello, Tamarit, J.L. and Lloveras, P. (2025) 'Finite-element study of a high-performance cascaded barocaloric cooler', Applied Thermal Engineering, 280, p. 128055.

# NUMERICAL ANALYSIS ON THE OPTIMIZATION OF AN HEAT RECOVERY CYCLE FOR AN ELASTOCALORIC DEVICE

**Luca Cirillo[(a)], Adriana Greco[(a)], Claudia Masselli[(a)], Lucrezia Verneau[(a)*]**

[(a)]Department of Industrial Engineering, University of Naples Federico II P.le Tecchio 80, 80125 Naples Italy

* corresponding author e-mail: lucrezia.verneau@unina.it; +39 3391052855

## ABSTRACT

This study presents a numerical investigation of a spiral-shaped elastocaloric regenerator operating under a Heat Recovery (HR) cycle (Qian *et al.*, 2015). The device consists of two spiral-shaped NiTi beds (length 100 mm) with windings of 0.3 mm and fluid channels of 0.15 mm (Cirillo *et al.*, 2026), connected by heat recovery pipes 200 mm long. The finite element method is used to model the device and investigate the influence of key operating and geometrical parameters. The operating frequency varies between 0.05 Hz and 0.15 Hz and the ratio between the HR duration and the fluid flow time is set to 1, 2, and 3. Five connecting pipe diameters, ranging from 3 mm to 9 mm, are also investigated. Results show that appropriate tuning of these parameters enhances both the cooling capacity and overall efficiency, providing design guidelines for advanced elastocaloric regenerators in solid-state cooling applications.

**Keywords:** Elastocaloric cooling, Heat Recovery cycle, geometry optimization, thermal analysis, numerical modelling

**References:**

Cirillo, L. et al. (2026) “Numerical simulations for regenerator optimization in an experimental elastocaloric cooling prototype based on shape memory alloys,” Energy Conversion and Management, 348, p. 120616. Available at: https://doi.org/10.1016/J.ENCONMAN.2025.120616.

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# INFLUENCE OF LOADING AND UNLOADING PROFILES ON AN ACTIVE ELASTOCALORIC REGENERATOR: A NUMERICAL STUDY

**Luca Cirillo[(a)*], Adriana Greco[(a)], Claudia Masselli[(a)], Vincenzo Orabona[(a)], Lucrezia Verneau[(a)]**

[(a)]Department of Industrial Engineering, University of Naples Federico II P.le Tecchio 80, 80125 Naples Italy

* corresponding author e-mail: luca.cirillo2@unina.it; +39 3355878553

## ABSTRACT

A transient numerical analysis was carried out to investigate the influence of different loading and unloading profiles—instantaneous, linear, and semi-parabolic—on the thermal performance of a spiral- shaped elastocaloric device. The model focuses solely on heat transfer within a 100 mm-long spiral section composed of alternating layers of elastocaloric material (0.30 mm) and water channels (0.15 mm). Each loading profile was applied for 0.2 s, corresponding to a rotation frequency of 1 Hz (Tušek et al., 2016; Cirillo et al., 2026). Results, expressed in terms of temperature span, cooling power, and coefficient of performance (COP), show that the ideal instantaneous loading case provides the highest thermal performance, while smoother profiles lead to slightly reduced effectiveness. Temperature field distributions further illustrate the impact of the stress evolution on transient heat exchange. These findings offer insights into the role of load temporal profiles in optimizing elastocaloric regenerators.

**Keywords:** Elastocaloric regenerator, heat transfer modeling, loading-unloading profile, thermal performance.

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# SMARTCOOL – MODELING AND SIMULATION OF ELASTOCALORIC MATERIAL BEHAVIOR FOR TRANSLATORY COOLING CONCEPTS

**David Zimmermann[(a)(b)], Lukas Ehl[(a)(b)], Franziska Louia[(b)], Stefan Seelecke[(b)], Paul Motzki[(a)(b)]**

[(a)] Center for Mechatronics and Automation Technology (ZeMA gGmbH),
Saarbruecken, 66121, Germany, david.zimmermann@uni-saarland.de

[(b)] Saarland University, Department of Systems Engineering Saarbruecken, 66123, Germany

## ABSTRACT

Elastocaloric cooling, exploiting the martensitic phase transformation in shape memory alloys, is considered one of the most promising alternatives to vapor-compression technology due to its high efficiency and environmental compatibility. While different heat transfer mechanisms and drive concepts have been explored, this work introduces a translatory elastocaloric machine concept enabling mechanical energy recuperation by simultaneously loading and unloading coupled elastocaloric elements based on Nickel-Titanium alloys.

The contribution focuses on the modeling and simulation of the elastocaloric material behavior under bidirectional loading. A thermodynamics-based model incorporating experimentally derived parameters is developed to describe key aspects such as mechanical responses, transformation behavior and latent heats. Based on these results, the simulation study enables the performance of the upcoming prototype to be assessed. These insights provide a pathway for optimizing elastocaloric system design and improving device efficiency in future elastocaloric cooling systems.

**Keywords:** Elastocalorics, Phase Transformation, Simulation, Modeling, Thermodynamics

**Acknowledgement:** SMArtCool is a project that has received funding from the Federal Ministry for Economic Affairs and Energy under Grant Agreement N. 03EN2123C

# ELASTOCALORIC MEASUREMENT APPARATUS FOR ELASTOMERS WITH BIMODAL (EXTENSION/COMPRESSION) STRAIN-RATE AND TEMPERATURE CONTROL

**Kenneth Rojo[(a)], Carlos Cosculluela[(a)], Pedro Téllez[(b)], Carlos Sánchez-Somolinos[(a)], Marco Evangelisti[(a)]**

[(a)] Instituto de Nanociencia y Materiales de Aragón (INMA), CSIC – Universidad de Zaragoza Zaragoza, 50009, Spain, kmrojo@unizar.es

[(b)] Servicio General de Apoyo a la Investigación (SAI), Universidad de Zaragoza Zaragoza, 50009, Spain

## ABSTRACT

The effects of strain-rate on the elastocaloric response have been extensively investigated for metallic materials (Tusek et al., 2018), (Schmidt et al., 2016), (Zhou et al., 2018), but such investigations are limited for elastomeric materials. To address this gap, we built a tensile apparatus that can separately set the strain-rate for extension and compression, while regulating the ambient temperature. The apparatus uses a belt-drive coupled to a variable-speed motor, enabling bidirectional control of strain, hold period, and strain-rate. The elastomer sample is housed in a PID-controlled heater coupled to a nitrogen-gas flux for temperature regulation, and its temperature is measured with infrared thermography. This setup allows us to design various elastocaloric cycles; an example is a low-rate extension followed by a high-rate compression, which minimizes material damage while maximizing the cooling effect. By allowing separate strain-rate control for extension and contraction, together with temperature control, the instrument provides a platform for a systematic investigation of efficient, long-lasting elastocaloric cycling programs for elastomers.

**Keywords:** elastocaloric effect, elastomer, strain-rate

**References:**

Tušek, J., Žerovnik, A., Čebron, M., Brojan, M., Žužek, B., Engelbrecht, K. and Cadelli, A., 2018. Elastocaloric effect vs fatigue life: Exploring the durability limits of Ni-Ti plates under pre-strain conditions for elastocaloric cooling. Acta Materialia, 150, pp.295-307. doi.org/10.1016/j.actamat.2018.03.032

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**Acknowledgement:** This work is funded under the MolCal project. MolCal is co-funded by the European Union under the Horizon Europe Programme (Grant agreement ID: 101119865) and UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee (EPSRC EP/Y036565/1 and EP/Y036948/1).

# THERMO-MECHANO-CALORIC INVESTIGATION OF CYCLIC TRAINING EFFECTS IN NITI-BASED ELASTOCALORIC MATERIALS

**Franziska Louia[(a)], Stefan Seelecke[(a)], Paul Motzki[(a)(b)]**

[(a)]Saarland University, Department of Systems Engineering Saarbruecken, 66123, Germany,
franziska.louia@uni-saarland.de

[(b)] Center for Mechatronics and Automation Technology (ZeMA gGmbH), Saarbruecken, 66121, Germany

## ABSTRACT

The emerging technology of Elastocalorics offers great potential for higher efficiency cooling based on solid-state materials such as Nickel-Titanium-based alloys. To ensure consistent performance of the alloys they are first subjected to a training procedure. This study focuses on the training of superelastic NiTi-based alloys, examining the evolution of their thermo-mechano-caloric behavior under cyclic loading. A combined experimental approach is applied to determine evolving latent heats under mechanical load, enabling the observation of its real-time variation during training. Controlled mechanical cycling was performed to quantify changes in transformation stresses, hysteresis shape and area, and residual strain, while infrared thermography captured the coupled thermal response. The results reveal characteristic progressive modifications in latent heat release and absorption, closely linked to the stabilization of transformation behavior. This approach provides novel insights into how repeated loading alters both mechanical and thermal performance as well as the efficiency of NiTi-based alloys.

**Keywords:** elastocalorics, latent heats, training procedure, experimental

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# PRESSURE-INDUCED MEASUREMENTS OF BAROCALORIC EFFECT

**Tomaž Pšeničnik[(a)], Andrej Žerovnik[(a)], Miha Brojan[(a)], Jaka Tušek[(a)]**
[(a)] Faculty of Mechanical Engineering, University of Ljubljana Ljubljana, 1000, Slovenia,
tomaz.psenicnik@fs.uni-lj.si

## ABSTRACT

Barocaloric effects in solid materials have recently gained attention as a promising route toward environmentally friendly solid-state cooling. Accurate characterization is essential for understanding material performance under realistic operating conditions. The most common method—differential scanning calorimetry with pressure cells—probes temperature-induced transitions, whereas barocaloric devices rely on pressure-induced effects. Here, we present a novel experimental setup capable of performing pressure-induced measurements at various temperatures and pressure rates, reaching pressures up to 2 kbar. The setup enables both direct and indirect characterization of the barocaloric effect, providing measurements of adiabatic temperature and isothermal entropy changes. Initial tests performed with silicone rubber demonstrated adiabatic temperature changes of around 10 K at 1 kbar, confirming the setup's reliability and sensitivity. This approach offers a powerful tool for evaluating barocaloric materials and advancing the development of high-performance solid-state refrigeration technologies.

**Keywords:** barocaloric effect, pressure-induced transition, adiabatic temperature change

**Acknowledgement:** This work was supported by the Slovenian Research Agency (project no. J2-4478) and by the European Union's Horizon Europe EIC Pathfinder Challenge (grant agreement No. 101161137).

# P-T STRUCTURAL CHARACTERIZATION OF SPIN CROSSOVER COMPOUND FE(PYRAZINE)[FE(CN)$_5$(NO)]

**Maxime Deutsch[(a)], Dorsaf Gheries[(a)], Dominik Schaniel[(a)]**

[(a)] CRM2, Lorraine University

Vandoeuvre-lès-Nancy,54506, France, maxime.deutsch@univ-lorraine.fr

## ABSTRACT

Solid-state barocaloric refrigeration is an unconventional refrigeration principle, based on the barocaloric effect which causes reversible thermal (temperature and entropy) changes related to volume changes in solid-state materials induced by applied hydrostatic pressure. Among the barocaloric compound Spin crossover (SCO) materials widely studied for their potential applications in molecular switches, memory devices, sensors are promising candidate in order to build solid state barocaloric refrigerator. SCO compounds showing 1$^{st}$ order spin phase transition, which are mostly based on common Earth-abundant elements such as iron, will allow to avoid the use of harmful/dangerous and of critical raw materials such as rare-earth elements.

In order to optimize the properties of these compounds, a thorough understanding of their structures and phase diagram is essential. Here, we report a structural study of one of these compounds, (the Fe(pyrazine)[Fe(CN)$_5$(NO)]) (Plasencia et al., 2021), under both pressure and temperature, showing spin phase transition under both constraints.

**Keywords:** High pressure, Spin crossover, barocaloric, X-ray diffraction

**References:** Plasencia, Y., Avila, Y., Rodríguez-Hernández, J., Ávila, M., Reguera, E., 2021. Journal of Physics and Chemistry of Solids 150, 109843. https://doi.org/10.1016/j.jpcs.2020.109843

**Acknowledgement:** FROSTBIT has received funding from the European Innovation Council (EIC) under Horizon Europe Research and Innovation Programme grant agreement No 101161137 and additional funding from UKRI. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EISMEA. Neither the European Union nor the granting authority can be held responsible for them.

# GIANT MECHANOCALORIC EFFECTS IN CONFINED SPIN-CROSSOVER COMPOUNDS UNDER UNIAXIAL LOADING: TRANSFERABLE DESIGN RULES

**Enric Stern-Taulats[(a)], Kübra Gürpinar[(b, c)], Klara Lünser[(d)], Eyüp Kavak[(c, e)], Sinecan I. Bozkus[(b, f)], Baris Emre[(e)], Orhan Atakol[(b)], Marcel Porta[(g)], Antoni Planes[(a)], Eduard Vives[(a)], Alejandro Salvatori[(h)], Pol Lloveras[(h)], Josep-Lluís Tamarit[(h)], Lluís Mañosa[(a)]**

[(a)]Departament de Física de la Matèria Condensada, Facultat de Física, Universitat de Barcelona. 08028 Barcelona, Catalonia. enric.stern@fmc.ub.edu

[(b)]Department of Chemistry, Faculty of Science, Ankara University. Ankara, 06100, Türkiye

[(c)]Graduate School of Natural and Applied Sciences, Ankara University. Ankara 06100, Türkiye

[(d)]Institute for Energy Materials Processes. Universität Duisburg-Essen. 47259 Duisburg, Germany

[(e)]Department of Engineering Physics, Faculty of Engineering, Ankara University, Ankara, 06100, Türkiye

[(f)]Department of Forensic Sciences, Gendarmerie and Coast Guard Academy, Ankara University. Ankara, 06906, Türkiye

[(g)]Departament de Física Quàntica i Astrofísica. Facultat de Física, Universitat de Barcelona. 08028, Barcelona, Catalonia

[(h)]Grup de Caracterització de Materials, Departament de Física, EEBE and Barcelona Research Center in Multiscale Science and Engineering, Universitat Politècnica de Catalunya. Barcelona, 08019, Catalonia

## ABSTRACT

Barocaloric materials are outstanding, but integration is hampered by generating and containing high hydrostatic pressures with thick-walled vessels, seals, and pressure-transmitting media (Lloveras et al., 2021). With a laterally confined piston-cylinder imposing a controlled stress state between hydrostatic and free-uniaxial, we drive giant mechanocaloric effects in the spin-crossover complex $Fe(htrz)_2(trz)(BF_4)$ using moderate uniaxial loads (~2 kN). Combined calorimetric and dilatometric measurements give $|\Delta S| = 130$ J kg$^{-1}$ K$^{-1}$ and $|\Delta T| = 6.8$ K at 95 MPa; at 160 MPa, $|\Delta T|$ reaches 14.4 K, comparable to hydrostatic barocalorics. Because SCO transitions carry large entropies (Sandeman et al., 2016), (Vallone et al., 2019) (Romanini et al., 2021), the uniaxial route transfers more heat at lower stress than elastocaloric prototypes, reducing operational work and boosting COP (Moya et al., 2015) (Qian et al., 2023). Lower peak stress also permits thinner, thermally conductive confinement walls, improving heat exchange and enabling higher cycling frequencies. Together this enables compact solid-state cooling units and guides design: choose the force mode and confinement that maximise coupling and stabilise the load path.

**Keywords:** Mechanocaloric effects, elastocaloric effects, barocaloric effects, Spin-crossover compounds, Uniaxial loading, Confinement, Solid-state cooling.

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**Acknowledgement:** We acknowledge support from MCIN/AEI/10.13039/501100011033 (PID2024-161052NA-I00, RYC2023-043444-I, PID2023-146623NB-I00), co-funded by the European Union (ERDF/FEDER), the "Maria de Maeztu" Programme (CEX2023-001300-M), the Generalitat de Catalunya (2021SGR-00328, 2021SGR-00343), and TUBITAK (MFAG-121F151, MFAG-118F128, 1059B142300156). J.L.T. acknowledges the ICREA Academia programme.

# COLOSSAL BAROCALORIC EFFECTS IN SPIN CROSSOVER COMPOUNDS WITH A SHARP SPIN TRANSITION

**Alba Prats[(a)], Mounir Akoudad[(a)], Mario M. Pacheco[(b)], Alvar Torelló[(a)], Michela Romanini[(a)], Pol Lloveras[(a)], Enric Stern Taulats[(c)], Catalin Popescu[(d)], Ana Belén Gaspar[(b)], Lluís Mañosa[(c)], Josep-Lluís Tamarit[(a)], Adrià Gràcia Condal[(a)]**

[(a)] Group of Characterization of Materials, Department of Physics, Polytechnic University of Catalonia (UPC), Av. Eduard Maristany 10-14, 08019, Barcelona, Spain. email: adria.gracia.condal@upc.edu

[(b)] Group of Iron based Molecular Switches, Molecular Science Institute (ICMol), University of Valencia (UV), c/ Catedrático Jose Beltran Martínez 2, 46980, Paterna, Spain.

[(c)]Group of Functional Materials and Phase Transitions, Department of Condensed Matter Physics, University of Barcelona (UB), c/Martí i Franquès 1, 08028, Barcelona, Spain,

[(d)] CELLS-ALBA synchrotron, c/ de la Llum 2-26, 08290, Cerdanyola del Valles, Spain.

## ABSTRACT

Recently, spin crossover (SCO) compounds have emerged as promising solid-state barocaloric refrigerants (Sandeman et al., 2016), (Vallone et al., 2019). In these compounds, a phase transition from a high-spin (HS) to a low-spin (LS) state that can be accompanied by a large volume change (Gütlich et al., 2013), (Shatruk et al., 2015) is behind the emergence of barocaloric effects. In this work, we characterized the barocaloric response of two SCO: {Fe(3-Fpy)2[Pd(CN)4]} and {Fe(3-Fpy)2[Pt(CN)4]} (abbreviated as FPd and FPt, respectively) by means of high-pressure calorimetry and X-ray powder diffraction. Both compounds exhibit a sharp HS-LS phase transition with an associated transition entropy change of $\Delta S_t \approx 200$ and $170$ J⁄kg · K, respectively, being the highest values reported so far for the family of SCO compounds (Martinez et al., 2009). Their HS-LS phase transition is strongly sensitive to the applied pressure and shift at a rate of $dT_t/dp \approx 0.21 - 0.22$ K⁄MPa. We have found that both compounds exhibit colossal barocaloric effects below room temperature, which become reversible under moderate pressures of $p_{rev} \approx 100$ MPa.

**Keywords:** spin crossover, colossal barocaloric effects, high-pressure calorimetry, high-pressure x-ray powder diffraction.

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## S15 Other Effects KOSOVEL HALL

Chair **Urban Tomc** · Co-chair **Grega Belšak** · Help **Izak Oberčkal Pluško**

16:45 Theoretical framework of acoustically enhanced solid–gas adsorption refrigeration
**Tianqi Wu** · *Technical Institute of Physics and Chemistry, Chinese Academy of Sciences*

16:57 Modelling of thermoacoustic generator in TCCbuilder
**Izak Oberčkal Pluško** · *FME, University of Ljubljana*

17:09 Sn-based metallic phase change materials for the development of thermal energy storage systems
**Matteo Molteni** · *Politecnico di Milano*

17:21 Role of polymer electrodes for gelified thermoelectrochemical redox systems for waste-heat recovery applications
**Momna Haq** · *CHOSE — University of Rome Tor Vergata*

17:33 Direct calorimetric evaluation of scalable thermophotovoltaics: from cells to modules
**Pablo García-Linares** · *Universidad Politécnica de Madrid*

17:45 Introducing an artificial neural network for predicting the performance of thermophotovoltaic devices
**Myrto Zeneli** · *UPM*

# THEORETICAL FRAMWORK OF ACOUSTICALLY ENHANCED SOLID–GAS ADSORPTION REFRIGERATION

**Tianqi Wu[a,b], Yupeng Yang[a,b], Ercang Luo[a,b], Rui Yang[a]**

[a] State Key Laboratory of Cryogenic Science and Technology, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, 100190, China, yangrui@mail.ipc.ac.cn

[b] University of Chinese Academy of Sciences, Beijing 100049, China, yangrui@mail.ipc.ac.cn

## ABSTRACT

Solid–gas adsorption refrigeration is an alternative to vapor compression refrigeration. Herein, we conceive the idea of acoustically enhanced solid–gas adsorption refrigeration, combining adsorption refrigeration with thermoacoustic effects. Since sorption kinetics is governed by variations of pressure and temperature that are intrinsic to acoustic waves, the combination is physically reasonable. The resulting adsorption refrigeration micro-cycles are acoustically driven, thereby eliminating the complex structure in conventional adsorption systems, with extra thermoacoustic cooling effects. We develop a theory and apply it to evaluate cooling capacity and coefficient of performance of the combined refrigeration cycle. Results show that, under appropriate acoustic fields and with suitable adsorbent-adsorbate pairs, the refrigeration is improved considerably compared to standalone adsorption or thermoacoustic refrigeration, verifying that acoustic oscillations can effectively drive, and significantly enhance adsorption refrigeration. This exploration builds the theoretical framework for the acoustically enhanced solid-gas adsorption refrigeration.

**Keywords:** solid–gas adsorption refrigeration, thermoacoustic refrigeration, Langmuir kinetics

**References:**

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# MODELING OF THERMOACOUSTIC GENERATOR IN TCCBUILDER

**Izak Oberčkal Pluško[a], Harini Nivetha Raja[b], Grega Belšak[a], Jingyuan Xu[b], Katja Vozel[a], Andrej Kitanovski[a], Katja Klinar [a]**

[a]Faculty of Mechanical Engineering, University of Ljubljana Ljubljana, 1000 Ljubljana, Slovenia,
katja.klinar@fs.uni-lj.si

[b]Karlsruhe Institute of Technology, Institute of Microstructure Technology, Hermann-von-Helmholtz-Platz 1,
76344 Eggenstein-Leopoldshafen, Germany

## ABSTRACT

Thermoacoustic power generation represents an innovative energy-harvesting approach characterized by high reliability, low cost, and environmental friendliness (Xiao et al., 2023). Within the THERMINATOR project, funded by the European Union's Horizon Europe programme under Grant Agreement No. 10119283, we are developing an electro-thermal energy converter that combines thermoacoustic and electrocaloric principles. To analyse the interaction and integration of these two technologies—eventually leading to a working prototype—the first step focuses on modelling. The hybrid system is modelled using TCCbuilder, an open-source simulation tool for time-dependent one-dimensional analysis of thermal control circuits (Vozel et al., 2024).

In this paper, we present one of the four modules being developed within this project: the thermoacoustic generator module. The module operates as a black-box model, considering only its inputs and outputs. These are carefully defined and connected through specific mathematical functions derived from the literature, describing the device's performance. In this paper we demonstrate the model and present a case study comparing various configurations and assessing their performance relative to that of individual thermoacoustic generators.

**Keywords:** thermoacoustic, TCCbuilder, generator, heat transfer, energy efficiency

**References:**

L. Xiao et al., "Time-domain acoustic-electrical analogy investigation on a high-power traveling-wave thermoacoustic electric generator," Energy, vol. 263, p. 126088, Jan. 2023, doi: 10.1016/j.energy.2022.126088.

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# SN-BASED METALLIC PHASE CHANGE MATERIALS FOR THE DEVELOPMENT OF THERMAL ENERGY STORAGE SYSTEMS

**M. Molteni[a], S. Marola[a], F. Villa[b], P. Bassani[b], E. Gariboldi[a]**

[a] Politecnico di Milano, Department of Mechanical Engineering, Milano, 20156, Italy, matteo1.molteni@polimi.it, silvia.marola@polimi.it, elisabetta.gariboldi@polimi.it

[b] CNR ICMATE, Lecco, 23900, Italy, paola.bassani@cnr.it, francesca.villa@cnr.it

## ABSTRACT

Phase Change Materials (PCMs) are emerging as efficient solutions for the development of thermal energy storage and management systems. Thanks to their high thermal conductivity and wide region of phase transition temperatures, metallic PCMs are suitable materials for effective latent heat storage solutions. In this work, fully-metallic PCMs composed of a Sn-based active phase (melting temperature equal to 230°C) dispersed within a passive Al-based matrix, thought for Thermal Energy Storage purposes, were produced by induction melting. Thermal properties were modelled and compared to results from experimental tests. The microstructure of the alloys were analyzed by optical and scanning electron microscopy and energy dispersive x- ray analysis. Moreover, the effect of thermal cycling was investigated to assess the PCMs stability in view of technological solutions design. The discussed results aim at providing a guideline for the development of efficient thermal energy storage systems based on advanced metallic PCMs.

**Keywords:** thermal energy storage, phase change materials, Al-Sn alloys

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# ROLE OF POLYMER ELECTRODES FOR GELIFIED THERMOELECTROCHEMICAL REDOX SYSTEMS FOR WASTE-HEAT RECOVERY APPLICATIONS

**M. Haq**[a], **E. Marchini**[b], **R. Boaretto**[b], **S. Carli**[b], **S. Caramori**[b], **C. Barolo**[c], **A. Reale**[a*]

(a) Department of Electronic Engineering, CHOSE—Centre for Hybrid and Organic Solar Energy, University of Rome Tor Vergata, via del Politecnico 1, 00133 Rome, Italy

(b) Department of Chemical, Pharmaceutical and Agricultural Sciences, University of Ferrara, Via Luigi Borsari 46, 44121 Ferrara, ITALY.

(c) Department of Chemistry and NIS Interdepartmental Centre, University of Turin, Via Pietro Giuria 7, Torino, 10125, Italy Corresponding Author: reale@uniroma2.it, Tel: +390672597372

## ABSTRACT

Thermogalvanic cells (TGCs) have emerged as a promising technology for converting low-grade thermal energy into electricity. Liquid electrolytes often struggle with leakage and rigidity issues that restrict their use in flexible and wearable applications. Gel electrolytes have emerged as an ideal solution, especially when ionic liquids are incorporated into gel matrix (Lee et al., 2025).

We present a Gel Electrolyte TGC device using 100 mM Co(II)/Co(III) electrolytes and PEDOT PH1000(10% DMSO) based electrodes on both Glass-FTO and PET-ITO. The device has shown Seebeck coefficient ranging from 1100 µV/K to 1300 µV/K. We verified that the electrochemical Seebeck coefficient depends on electrode distances. In the range from 200 µm to 2mm, Seebeck rose from -1100 µV/K to -1600 µV/K. Electrical conductivity reached up to 0.31 mS/cm, highlighting the material's potential for high-performance thermoelectric applications. We are now investigating the impact of different Co(II)/Co(III) concentrations and electrodes made through various deposition techniques on the device performance (Buckingham et al., 2021).

**Keywords:** Seebeck Coefficient, Thermogalvanic Cell, Co(II)/Co(III) Electrolyte, Energy Harvesting.

**References:**

Buckingham, M.A., Laws, K., Li, H., Kuang, Y. and Aldous, L. (2021) *Cell Reports Physical Science*, article 100510

Lee, C.-Y., Hong, S.-H. and Liu, C.-L. (2025) *Macromolecular Rapid Communications*, 46, article 2400837

**Acknowledgments:** This work was partially supported by PTR25-27 Ricerca di Sistema - WP3 – LA3.5 Moduli termoelettrici e termoelettrogalvanici per il recupero di energia negli edifici orientati ad applicazioni flessibili.

# DIRECT CALORIMETRIC EVALUATION OF SCALABLE THERMOPHOTOVOLTAICS: FROM CELLS TO MODULES

**Esther López[(a)], Juan Villa[(a)], Pablo García-Linares[(a)], Nicolas Loubet[(b)], Myrto Zeneli[(a)], Alvaro M. Medrano[(a)], Daniel Milovich[(a,b)], Ignacio Izquierdo[(a,b)], Saad Akhtar[(a)], Alejandro Datas[(a)]***

[(a)] Instituto de Energía Solar – Universidad Politécnica de Madrid Madrid, 28040, Spain, a.datas@upm.es

[(b)]Thermophoton S.L., Madrid, 28290, Spain, contact@thermophoton.com

## ABSTRACT

Thermophotovoltaics (TPV) convert thermal radiation directly into electricity through the photovoltaic effect. Conventional TPV systems combine a thermal emitter with a closely coupled infrared-sensitive photovoltaic cell. Although recent studies report efficiencies up to 44% (Roy-Layinde et al., 2024)—the highest among solid-state heat engines—many rely on semi-empirical models and millimeter-scale devices, leaving open questions about practical performance and scalability. Here, we address these challenges through two advances: (1) fabrication of large-area (1 cm²) TPV cells based on Ge and InGaAs semiconductors, and (2) direct efficiency measurement using high-temperature calorimetry under high view-factor conditions (López et al., 2023). We demonstrate efficiencies of 7–12% for Ge and 25–30% for InGaAs devices, achieving power densities of 1–5 W/cm² at emitter temperatures up to 1800 °C. Preliminary TPV module integration results show over 100 W output, advancing scalable TPV systems for high-temperature thermal battery applications (Datas et al., 2022).

**Keywords:** thermophotovoltaics, calorimetry, efficiency measurement, semiconductor devices

**References:**

Datas, A., López-Ceballos, A., López, E., Ramos, A., del Cañizo, C., 2022. Latent heat thermophotovoltaic batteries. Joule 6, 418–443. https://doi.org/10.1016/j.joule.2022.01.010

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Roy-Layinde, B., Lim, J., Arneson, C., Forrest, S.R., Lenert, A., 2024. High-efficiency air-bridge thermophotovoltaic cells. Joule 8, 2135–2145. https://doi.org/10.1016/j.joule.2024.05.002

**Acknowledgement:** The authors acknowledge financial support from the Spanish Research State Agency (MCIN/AEI/10.13039/501100011033) through the project PID2023-150209OB-C21 (TOMATE). The work has been also funded by the projects THERMOBAT, SUNSON and BLAZETEC, from the European Commission under grant agreements 10105754, 101083827, and 101160724, respectively. The sole responsibility for the content of this publication lies with the authors. It does not necessarily reflect the views of the European Union. Neither the REA nor the European Commission is responsible for any use that may be made of the information contained herein. D. Milovich and I. Izquierdo acknowledges Comunidad de Madrid for financial support through the program of Industrial Doctorates (IND2023/AMB-28905 and IND2022/AMB-23530, respectively). Myrto Zeneli acknowledges the Spanish Ministry of Science, Innovation and Universities (MCIU), the State Research Agency (AEI, DOI: 10.13039/501100011033), and the European Social Fund Plus (FSE+), for the Juan de la Cierva-Formación contract (JDC2023-052884-I). This work has also been supported by the Community of Madrid through the R&D Program TEC-2024/ECO-72 (4EVERPV-CM), granted by the Dirección General de Investigación e Innovación Tecnológica under Order 3177/2024.

# INTRODUCING AN ARTIFICIAL NEURAL NETWORK FOR PREDICTING THE PERFORMANCE OF THERMOPHOTOVOLTAIC DEVICES

**Myrto Zeneli**[(a)*], **Alejandro Datas**[(a)]

[(a)] Instituto de Energía Solar – Universidad Politécnica de Madrid Madrid, 28040, Spain, m.zeneli@upm.es

## ABSTRACT

Thermophotovoltaic (TPV) devices convert thermal radiation into electricity using a pair of an emitting and an absorbing (thermophotovoltaic cell) surface. Selecting suitable optoelectrical material properties and operating/design parameters is crucial to achieve high conversion efficiencies in such devices. Simulation tools can assist on this process, however, most of the state-of-the-art models are either limited in their predictions or time consuming. This work introduces a reduced order model based on an artificial-neural network (ANN) trained with data from an electric model describing the performance of TPV devices. The electric model (Datas et al., 2015) uses inputs, such as the emitter and cell temperatures, emitter emissivity, and back-surface reflectivity, providing valuable insight into the TPV conversion efficiency. ANN-based multivariable polynomial functions are then trained in Matlab™ using data from the produced datasets, with fitting performed through the Levenberg– Marquardt algorithm. The resulting functions enable fast and accurate estimation of TPVs performance.

**Keywords:** artificial neural networks; thermophotovoltaic device; electric model; reduced-order model

**References:**

Datas, A., 2015. Optimum semiconductor bandgaps in single junction and multijunction thermophotovoltaic converters. Solar Energy Materials and Solar Cells 134, 275-290. https://doi.org/10.1016/j.solmat.2014.11.049

**Acknowledgement:** This work was supported by the Spanish Ministry of Science, Innovation and Universities (MCIU), the State Research Agency, and the European Social Fund Plus (FSE+), under the Juan de la Cierva-Formación contract (JDC2023-052884-I).

## S16 Magnetocalorics & Thermomagnetics LINHART HALL

Chair **Tsuyoshi Kawanami** · Co-chair **Sergiu Lionte** · Help **Kamyar Dobakhti**

11:30 Hypereg: High-frequency magnetocaloric regenerator
**Andrej Kitanovski** · *FME, University of Ljubljana*

11:42 Coupled magnetic and electric model of a thermomagnetic energy harvester
**Aske Nilsson** · *Technical University of Denmark (DTU)*

11:54 Research on a magnetocaloric heat pump design preventing fluid mixing in AMR operation
**Daiki Endo** · *Meiji University*

12:06 Design of a magnetocaloric heatpipe with 20 segments
**Jan Schipper** · *Universität Stuttgart*

12:18 A compact design portfolio for magnetocaloric refrigerators and heat pumps
**Jierong Liang** · *Helmholtz-Zentrum Dresden-Rossendorf*

# HYPEREG: HIGH-FREQUENCY MAGNETOCALORIC REGENERATOR

**Andrej Kitanovski[a,*], Katja Klinar[a], Jure Javornik[a], Simon Nosan[a], Jakob Perne[a], Simon Bogić[a], Blaž Jagodic[a], Urban Tomc[a]**

[b]University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva 6, 1000 Ljubljana, Slovenia,

*Corresponding author, email: andrej.kitanovski@fs.uni-lj.si

## ABSTRACT

Magnetic refrigeration is an efficient, environmentally friendly alternative to vapor-compression systems, using magnetocaloric materials in active magnetic regenerators (AMRs). However, AMRs typically operate efficiently only below 5 Hz due to heat-transfer limits and fluid losses, so adequate cooling power at low frequency demands large masses of magnetocaloric material and permanent magnets, increasing cost and slowing commercialization.

To address these challenges, we present an experimental proof-of-concept of Hypereg (Kitanovski et al., 2024), (Klinar et al., 2024), a high-frequency AMR capable of operating at significantly higher frequencies (above 10 Hz). To harness Hypereg's potential, a novel, motionless electro-permanent magnetic field source (Tomc et al., 2023) was developed, generating a 1.5 T magnetic field change at frequencies up to 50 Hz, while a redesigned hydraulic system enables heat-transfer-fluid oscillation up to 20 Hz. These preliminary findings mark an important first step toward the development of high power-density magnetocaloric devices, as well as other caloric technologies. Further design challenges will also be outlined in this contribution.

**Keywords:** Active Magnetic Regenerator, High-Frequency, Magnetocaloric, Magnetic Field Source, Power-Density

**References:**

Kitanovski, A., Tomc, U., Klinar, K. et al. (2024) *Method for heat transfer in the embedded structure of a heat regenerator and the design thereof*, United States patent US 12,000,663 B2, 4 June. Alexandria: United States Patent and Trademark Office.

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Tomc, U., Nosan, S., Klinar, K. and Kitanovski, A. (2023) 'Towards powerful magnetocaloric devices with static electro-permanent magnets', *Journal of Advanced Research*, 45, pp. 157–181. doi: 10.1016/j.jare.2022.05.001.

# COUPLED MAGNETIC AND ELECTRIC MODEL OF A THERMOMAGNETIC ENERGY HARVESTER

**Aske Chris Nilsson[(a)], Andrea Roberto Insinga[(a)], Salvatore De Angelis[(a)], Rasmus Bjørk[(a)]**

[(A)] Department of Energy Conversion and Storage, Technical University of Denmark (DTU)
Kongens Lyngby, Agnes Nielsens Vej B. 301,
2800, Denmark, achni@dtu.dk

## ABSTRACT

This work presents an analytical and numerical model of a thermomagnetic generator (TMG) that calculates power by explicitly coupling the TMG's magnetic and electric circuits. The governing ordinary differential equations of the TMG are derived. The analytical solution of these, valid for systems with small relative variations of magnetic permeability, shows that TMG power has a linear dependence on coil volume, independent of the specific combination of wire radius and coil turns, while the full numerical model always applies. Utilizing the model, we determine values for the load impedance that maximize power, requiring the implementation of a load capacitor matching the two coil's self-inductance. The model is validated with experimental data and finally used to study prototype TMGs presented in literature, where we show that the power of these literature TMGs can be increased by a factor of 10-400 times, had larger coils been used in the prototypes (Bahl et al., 2024), (Dzekan et al., 2021), (Liu et al., 2023), (Waske et al., 2019).

**Keywords:** Thermomagnetic energy harvesting, Thermomagnetic materials, Magnetic circuit, Electric circuit, Finite element method, Numerical modeling

**References:**

Bahl, C. et al. (2024) 'Design, optimization and operation of a high power thermomagnetic harvester', Applied Energy, 376, article 124304. doi: 10.1016/j.apenergy.2024.124304.

Dzekan, D., Diestel, A., Berger, D., Nielsch, K. and Fähler, S. (2021) 'Can gadolinium compete with La-Fe-Co-Si in a thermomagnetic generator?', Science and Technology of Advanced Materials, 22(1), pp. 643–657. doi: 10.1080/14686996.2021.1957657.

Liu, X., Chen, H., Huang, J. et al. (2023) 'High-performance thermomagnetic generator controlled by a magnetocaloric switch', Nature Communications, 14, article 4811. doi: 10.1038/s41467-023-40634-x.

Waske, A., Dzekan, D., Sellschopp, K. et al. (2019) 'Energy harvesting near room temperature using a thermomagnetic generator with a pretzel-like magnetic flux topology', Nature Energy, 4, pp. 68–74. doi: 10.1038/s41560-018-0306-x.

# RESEARCH ON A MAGNETOCALORIC HEAT PUMP DESIGN PREVENTING FLUID MIXING IN AMR OPERATION

**Daiki Endo[(a)], Kunihiko Hayashi[(b)], Tsuyoshi Kawanami[(a)]**

[(a)] School of Science and Technology, Meiji University
1-1-1 Higashi-Mita, Tama-ku, Kawasaki-shi, Kanagawa 214-8571 Japan, kawanami@meiji.ac.jp
[(b)] Toyota Technical Center Higashi-Fuji, Toyota Motor Corporation
1200, Mishuku, Susono-shi, Shizuoka 410-1193 Japan, kunihiko_hayashi@mail.toyota.co.jp

## ABSTRACT

Magnetocaloric heat pumps based on the active magnetic regenerator (AMR) cycle utilize the magnetocaloric effect to obtain heated and cooled fluids at the hot and cold ends, respectively, through a reciprocating flow of heat-transfer fluid. However, this bidirectional operation causes mixing between the high- and low-temperature streams, which limits the achievable temperature span. In this study, we propose a unidirectional-flow configuration in which the heat-transfer fluid continuously carries heat away from the magnetocaloric material (MCM), thereby preventing mixing between the hot and cold ends. Thermal storage media are introduced on both sides to alternately store and release heat, allowing each end to remain thermally independent. As a result, the proposed system can efficiently establish and maintain a temperature span without back-mixing losses, offering a promising pathway toward higher performance and practical implementation of magnetocaloric heat-pump technology.

**Keywords:** magnetocaloric heat pump, AMR, reciprocating flow, unidirectional-flow, MCM

**References:**

J. Romero, R. Ferreiro et al, (2013), Experimental analysis of a reciprocating magnetic refrigeration prototype, international journal of refrigeration, vol. 36, pp. 1388-1398, http://dx.doi.org/10.1016/j.ijrefrig.2013.01.008

# DESIGN OF A MAGNETOCALORIC HEATPIPE WITH 20 SEGMENTS

**Jan Schipper[a,b], Sabrina Unmüßig[b], Christian Vogel, Kilian Bartholomé[b], Stefan Mönch[a], Jürgen Wöllenstein[b]**

[a] Universität Stuttgart Stuttgart, 70569, Germany

[b]Fraunhofer IPM, Freiburg, 79110, Germany, jan.schipper@ipm.fraunhofer.de

## ABSTRACT

Active magnetocaloric heat pipes (AMH) are proposed as an alternative to active magnetocaloric regenerators (AMR). AMH use evaporation/condensation and passive check valves to rectify heat flow. This heat transfer method enables a higher power density and generates much lower pressure losses compared to the forced convection used by AMR. In this work we will focus on the development of our latest prototype. Which is a cascade consisting of 20 segments filled with 2 kg of Gd. Several components of this prototype like the magnet system and the check-valves have been improved compared to previous prototypes. Even though only about 60 % of the segments were functional at the same time due to issues with the distribution of the liquid, this system achieved a maximum temperature span of 13.5K and a maximum cooling power of 235 W. At 10 K the system reached an exergetic efficiency of 17 %.

**Keywords:** magnetocaloric cooling, active magnetocaloric heat pipe, heat pump

**Acknowledgement:** BMWk Project MagMed2 (03EN2066A)

# A COMPACT DESIGN PORTFOLIO FOR MAGNETOCALORIC REFRIGERATORS AND HEAT PUMPS

**Jierong Liang[(a)], Dimitri Benke[(b)], Thomas Platte[(a)], Tim Sittig[(b)], Maximilian Fries[(b)], Tino Gottschall[(a)]**

[(a)] Dresden High Magnetic Field Laboratory (HLD-EMFL), Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany

[(b)] MAGNOTHERM Solutions GmbH, Pfungstädter Str. 102, 64297 Darmstadt, Germany

## ABSTRACT

In this work, we show a concise technology portfolio to support the early-stage design of magnetocaloric refrigerators and heat pumps (Liang et al., 2020). The portfolio comprises three integrated components: (1) a dimensionless analytical model for rapid estimation of magnetocaloric material requirements; (2) a convolutional approach for coupling magnetic field distributions, material properties, and fluid flow characteristics to determine the optimal regenerator geometry; and (3) a second-law analysis tool that quantifies irreversibilities throughout the regenerator, enabling the rapid identification of efficiency losses, with particular emphasis on cryogenic regenerators employing compressible heat transfer fluids. The technology suite will be validated against both experimental data and a full-scale regenerator model (Diamantopoulos et al., 2025). Moreover, it is applicable to both room-temperature and cryogenic magnetocaloric systems (Kitanovski et al., 2020). This integrated portfolio represents a significant step toward the rapid, model-based development of next-generation magnetocaloric refrigeration and heat pump technologies.

**Keywords:** Active Magnetic Regenerator, Dimensionless Analysis, Convolution Operation, Thermodynamics.

**References:**

Diamantopoulos, T., Moreno-Ramírez, L.M., Franco, V. and Bjørk, R. (2025) International Journal of Refrigeration, 178. doi: 10.1016/j.ijrefrig.2025.07.005.

Kitanovski, A. (2020) Advanced Energy Materials, 10, article 1903741. doi: 10.1002/aenm.201903741.

Liang, J. et al. (2020) Applied Thermal Engineering, 181, article 115993. doi: 10.1016/j.applthermaleng.2020.115993.

*ORAL PRESENTATIONS*

## S17 Mechanocalorics & Thermomechanics KOSOVEL HALL

Chair **Paul Motzki** · Co-chair **Melony Dilshad** · Help **Benjamin Burgar**

11:30 Design and performance of a cam-disc-based elastocaloric device with four phase-shifted elastocaloric regenerators
**Andrej Žerovnik** · *Univerza v Ljubljani, Fakulteta za Strojništvo*

11:42 Non-uniformly shaped multi-layer elastocaloric regenerators
**Di Ma** · *School of Energy and Power Engineering, Xi'an Jiaotong University*

11:54 Proof-of-concept testing of novel neopentyl glycol barocaloric cooling device
**Pravinth Balthazar** · *University of Technology Sydney*

12:06 High-performance elastocaloric air cooling and dehumidification by shuttle-coiling actuation
**Xueshi Li** · *The Hong Kong University of Science and Technology*

12:18 High specific power elastocaloric systems — flat and compliant cooling systems through dielectric electroactive polymer actuator systems
**Paul Motzki** · *Saarland University*

# DESIGN AND PERFORMANCE OF A CAM-DISC-BASED ELASTOCALORIC DEVICE WITH FOUR PHASE-SHIFTED ELASTOCALORIC REGENERATOR

**Andrej Žerovnik, Žiga Ahčin, Stefano Dall`Olio, Simon Krašna, Miha Brojan, Jaka Tušek**

University of Ljubljana, Faculty of mechanical Engineering Ljubljana, SI- 1000, Slovenia, e-mail: andrej.zerovnik@fs.uni-lj.si

## ABSTRACT

Elastocaloric cooling has emerged as one of the most promising solid-state alternatives to conventional vapor-compression systems. While significant progress has been made in the development of elastocaloric materials and regenerators in recent years, the drive systems for loading elastocaloric elements have received comparatively little attention, despite their critical impact on overall performance. Here, we present the first integrated elastocaloric device that combines four elastocaloric regenerators made of NiTi tubes and a drive system that provides constant torque and work-recovery during the operation. The objective is to demonstrate an approach that optimizes work input to maximize system-level efficiency by utilizing the synergy between the mechanical response of the regenerators and the advanced drive concept. We describe the design, operation, and experimental characterization of the device, including measured temperature span, cooling/heating power and coefficient of performance (COP). The results demonstrate the potential for future compact, efficient, and scalable elastocaloric cooling systems.

**Keywords:** Elastocaloric, efficient drive system, constant-torque approach

**Acknowledgement:** This work was supported by the European Research Council under the Horizon 2020 program (ERC starting grant no. 803669 – SUPERCOOL project) and Horizon Europe program (ERC Proof-of-the- Concept grant no. 101158362 – E-CO-HEAT project).

# NON-UNIFORMLY SHAPED MULTI-LAYER ELASTOCALORIC REGENERATORS

**Di Ma[(a)], Guoqu Zhou[(a)], Ye Liu[(a)], Jianlin Yu[(a)], Zuozhou Chen[(b)], Ito Tamaki[(b)], Naoki Matsumura[(b)], Kazuhiro Furusho[(b)], Suxin Qian[(a)]**

[(a)]School of Energy and Power Engineering, Xi'an Jiaotong University Xi'an, 710049, China, qiansuxin@xjtu.edu.cn

[(b)]Technologies and Innovation Center, Daikin Industries, Ltd Nishi-Hitotsuya 1-1, Settsu, Osaka, 566-8585, Japan, zuozhou.chen@daikin.co.jp

## ABSTRACT

Elastocaloric (eC) cooling enjoyed fast development, however, its full potential has yet to be released, partially due to the inevitable inhomogeneous phase transition in eC materials. Inspired by the evergreen coniferous trees in nature, we report a non-uniformly shaped multi-layer eC regenerator that advances eC cooling by aligning geometry with stress distribution to address this challenge. The design strategically varies tube density across three layers to match the intrinsic stress profile, mitigating overstress and incomplete transitions. Using a single commercial-grade NiTi material, the regenerator achieved a 45.5 K load-free temperature span, surpassing the uniform-shaped baseline by 12.4%. This improvement is attributed to its non-uniform design, which boosts phase transition homogeneity by 66.4%. Besides, scalability was demonstrated via a reciprocating eC water chiller incorporating two regenerators, achieving 272.6 W cooling power at zero temperature span. This research showing that customized non-uniform shape and geometry philosophy is the future direction for eC cooling.

**Keywords:** Elastocaloric cooling regenerator, Inhomogeneous phase transition, Non-uniform geometry, Geometry-function matching principle

# PROOF-OF-CONCEPT TESTING OF NOVEL NEOPENTYL GLYCOL BAROCALORIC COOLING DEVICE

**Pravinth Balthazar[(a)], Mohammad S. Islam[(a)], Nick S. Bennett[(a)]**
[(a)] School of Mechanical and Mechatronic Engineering, University of Technology Sydney Ultimo, NSW 2007, Australia, Pravinth.Balthazar@uts.edu.au

## ABSTRACT

Rising global warming intensified the demand for alternative sustainable cooling technologies. Barocaloric refrigeration has emerged as a promising alternative, following the discovery of Neopentyl Glycol (NPG), which is comparable to R-134a(Aznar et al., 2020; Lloveras et al., 2019). Many researchers have investigated materials with colossal barocaloric effects (Kitanovski et al., 2015; Qian et al., 2016; Lloveras & Tamarit, 2021 and Cirillo et al., 2022), some focus on thermodynamic cycles (Dai et al., 2023) and numerical analyses (Qian et al. 2024). However, no barocaloric devices exist; magnetocaloric data were used to validate the model as a viable approach. The authors designed and built a 65 mm-diameter barocaloric device to test 20 g of NPG and demonstrate a proof of concept. This study measures the experimental phase transition temperature of NPG at 250, 300, and 350 MPa, comparing it with NaCl to demonstrate the barocaloric effect at 320 K. The cooling temperature span and refrigeration capacity will also be evaluated for each pressure-driven irreversible Brayton Barocaloric (BBR) cycle. Future research will examine barocaloric material's performance under varying heat source and sink temperatures at 350 MPa.

**Keywords:** NPG, Cooling Temperature Span, Refrigeration Capacity, Brayton Barocaloric refrigeration cycle

**References:**

Aznar, A., Lloveras, P., Barrio, M., Negrier, P., Planes, A., Mañosa, L., Mathur, N.D., Moya, X., Tamarit, J.-L., 2020. Reversible and irreversible colossal barocaloric effects in plastic crystals. J Mater Chem A Mater 8, 639–647. https://doi.org/10.1039/C9TA10947A

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Qian, S., Geng, Y., Wang, Y., Ling, J., Hwang, Y., Radermacher, R., Takeuchi, I., Cui, J., 2016. A review of elastocaloric cooling: Materials, cycles and system integrations. International Journal of Refrigeration 64, 1–19. https://doi.org/10.1016/j.ijrefrig.2015.12.001

# HIGH-PERFORMANCE ELASTOCALORIC AIR COOLING AND DEHUMIDIFICATION BY SHUTTLE-COILING ACTUATION

**Xueshi Li[(a)], Qingping Sun[(a)], Shuhuai Yao[(a)]**

[(a)] Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Kowloon, Hong Kong, 999077, China, meqpsun@ust.hk (Q. Sun), meshyao@ust.hk (S. Yao)

## ABSTRACT

Existing elastocaloric air cooling is limited by bulky and inefficient actuation systems (Ahčin et al., 2022), (Li et al., 2023), resulting in low metrics (compactness, cooling power, and efficiency). Here, we develop a shuttle-coiling actuation based on NiTi wire bending to improve these metrics. A cooling layer consists of NiTi wires and copper shuttle, and multilayer stacking forms a chamber in which the uncoiled wire segments remain cold (14.5 K drop) to cool airflow directly (Sharar et al., 2021), (Chen et al., 2022). A 42 L volume elastocaloric air cooler built on this architecture delivers 205 W cooling power with an electrical coefficient of performance up to 5.1. Furthermore, our device demonstrates a promising dehumidification performance, with a moisture removal rate of 3 L per day at 30°C room temperature and 80% relative humidity. These results reveal the importance of improving the elastocaloric air cooling by advancing actuations (Wang et al., 2023).

**Keywords:** Shape memory alloy, Elastocaloric cooling, Bending, Energy Efficiency, Dehumidification

**References:**

Ahčin, Ž., Dall'Olio, S., Žerovnik, A., Baškovič, U.Ž., Porenta, L., Kabirifar, P., Cerar, J., Zupan, S., Brojan, M., Klemenc, J. and Tušek, J. (2022) 'High-performance cooling and heat pumping based on fatigue-resistant elastocaloric effect in compression', Joule, 6, pp. 2338–2357. doi: 10.1016/j.joule.2022.08.011.

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# HIGH SPECIFIC POWER ELASTOCALORIC SYSTEMS – FLAT AND COMPLIANT COOLING SYSTEMS THROUGH DIELECTRIC ELECTROACTIVE POLYMER ACTUATOR SYSTEMS

**Paul Motzki, Daniel Bruch**

Smart Material Systems, ZeMA – Center for Mechatronics and Automation Technology, Saarland University
Saarbrücken, 66121, Germany, paul.motzki@uni-saarland.de, daniel.bruch@uni-saarland.de

Eschberger Weg 46; Tel: +49 681 857 87 13

## ABSTRACT

Research on Elastocaloric cooling and heating has been emerging in recent years due to its potential to reduce energy consumption and environmental impacts. The newly ERC-funded DEAcool project seeks to push this technology further by incorporating dielectric electroactive polymers (EAPs) as actuators in elastocaloric (EC) systems. Replacing conventional electric motors or hydraulic systems, EAP drive systems offer substantial reduction in both weight and space requirements without compromising energy efficiency and work output. This novel approach will significantly improve the specific power density of EC systems in terms of both volume and mass, and new completely flat geometries enabling new areas of application, including wearable medical cooling devices, portable vaccine and food preservation, climate control in automotive and aerospace industries, satellite component cooling, and textile-integrated cooling systems. The contribution presents first concepts, preliminary simulations and early experimental results of EAPs driving the deformation of Nickel-Titanium-based Elastocaloric materials.

**Keywords:** elastocaloric, cooling, dielectric elastomers, electroactive polymers, solid-state refrigerant

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# THERMAG XI 2026

*IIR International Conference on Solid-State Cooling, Heating, and Energy Harvesting*

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**Anita Yadav** · *University of Duisburg-Essen*

# NEW LOW CRITICALITY HIGH ENTROPY ALLOYS WITH IMPROVED MAGNETOCALORIC EFFECT AT ROOM TEMPERATURE

**Elisa Guisado-Arenas[(a)], Zhe Cui[(a)], Luis M. Moreno-Ramírez[(b)], Carlos Romero-Muñiz[(a)], Jia Yan Law[(a)], Victorino Franco[(a)]**

[(a)]Multidisciplinary Unit for Energy Science (MUFENS), Departamento de Física de la Materia Condensada, ICMS-CSIC, Universidad de Sevilla, Sevilla 41080, Spain, eguisado1@us.es

[(b)]Departamento de Electricidad y Electrónica, Universidad de Valladolid, Valladolid 47011, Spain

## ABSTRACT

Magnetic refrigeration is an energy-efficient alternative to traditional cooling, driven by global cooling demands and climate mitigation. Yet, widespread adoption is partly stalled by the dire trade-off between performance and material criticality (unstable supply chains and global market risks). We present a scalable paradigm shift by engineering the multicomponent high entropy alloys (HEAs) for large magnetocaloric effects without criticality issues. Our $Mn_{0.5}Fe_{0.5}Ni_{1-x}Cu_xSi$ system eliminates dependence on high-magnetic-moment rare earths and cobalt as well as critical-supply germanium. The desired magnetostructural transformation (MST), absent in MnNiSi, was successfully induced via Fe/Cu addition for $x \geq 0.15$. The optimized MST magnifies the magnetocaloric effect at room temperature, boosting performance by an astounding 300 % (compared to x=0). The x=0.20 alloy records an isothermal entropy change of 5.8 J $kg^{-1}$ $K^{-1}$ (2 T), the new global benchmark for non-critical magnetocaloric HEAs. Our findings provide the critical material foundation addressing supply stability and sustainable solid-state cooling.

**Keywords:** magnetocaloric effect, high entropy alloys, low material criticality, magnetostructural transformations

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# EXPERIMENTAL INVESTIGATION AND COMPARISON WITH THEORETICAL RESULTS OF A CU BASED QUATERNARY HEUSLER ALLOY

**M. Molteni[(a)], E. Gariboldi[(a)], P. Bassani[(b)]**

[(a)] Politecnico di Milano, Department of Mechanical Engineering Milano, 20156, Italy,
matteo1.molteni@polimi.it; elisabetta.gariboldi@polimi.it

[(b)]National Research Council of Italy, Institute of Condensed Matter Chemistry and Technologies for Energy, CNR-ICMATE

Lecco, 23900, Italy, paola.bassani@cnr.it

## ABSTRACT

Heusler alloy are of high interest due to their potential use in for solid state refrigeration. Focusing on Cu bearing Heusler alloys, the majority of the investigations on these materials, rely on theoretical calculations (Ma et al., 2017) and on magnetic characterization (Uhl et al., 1982), paying less attention to processing, heat treatments or thermal cycling on microstructural features that could impact to the performances of such materials.

The authors investigated a quaternary Heusler alloy, produced by arc-melting, both in the as produced and thermally cycled condition, trying to focus on microstructural features modification. Identification of a candidate Heusler alloy was based on available literature data, with target Curie temperature $T_C$»90°C.

Microstructure was analysed by OM, SEM observations, supported by XRD analyses. Additionally, DSC and DTA analyses were performed to provide preliminary indications of the presence of microstructural transformation. The results were then compared with the simulation- derived results to assess the reliability of predictions for the investigated system.

**Keywords:** Heusler alloys, Microstructural investigation, Thermal stability

**References:**

Ma, Y., Hao, H., Xin, Y., Luo, H., Liu, H., Meng, F. and Liu, E. (2017) 'Atomic ordering and magnetic properties of quaternary Heusler alloys NiCuMnZ (Z=In, Sn, Sb)', Intermetallics, 86, pp. 121–125. doi: 10.1016/j.intermet.2017.03.020.

Uhl, E. (1982) 'Magnetism in mixed Heusler alloys (Ni1-xCux)2MnSn', Monatshefte für Chemie/Chemical Monthly, 113, pp. 275–284. doi: 10.1007/BF00799554.

# A SPIN FRUSTRATED HOURGLASS {$GD_9$} MOLECULAR NANOMAGNET WITH UNUSUAL MAGNETOCALORIC PROPERTIES

**Marc Ubach I Cervera[(a)], Sai P. K. Panguluri[(b)], Eufemio Moreno-Pineda[(c), (e)], Concepción Molina-Jirón[(b), (c), (d)], Sagar Paul[(e)], Emmanouil K. Charkiolakis[(a)], David Gracia[(a)], Marco Affronte[(f)], Wolfgang Wernsdorfer[(b), (e)], Marco Evangelisti[(b)], Jürgen Schnack[(g)], and Mario Ruben[(b), (h)]**

[(a)] Instituto de Nanociencia y Materiales de Aragón (INMA), CSIC & Universidad de Zaragoza, 50009 Zaragoza, Spain

[(b)] Institute of Quantum Materials and Technologies (IQMT), Karlsruhe Institute of Technology (KIT), 76344 Eggenstein-Leopoldshafen, Germany

[(c)] Facultad de Ciencias Naturales, Exactas y Tecnología, Depto. de Química-Física, Universidad de Panamá, 0824 Panamá, Panama; Facultad de Ciencias Naturales, Exactas y Tecnología, Grupo de Investigación de Materiales, Universidad de Panamá, 0824 Panamá, Panamá

[(d)] Grupo de Investigación de Materiales and Facultad de Ciencias Naturales, Exactas y Tecnología, Depto. de Bioquímica,Universidad de Panamá, 0824 Panamá, Panama

[(e)] Physikalisches Institut, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany

[(f)] Dipartimento di Scienze Fisiche, Informatiche e Matematiche, Universita di Modena e Reggio Emilia, 41125 Modena, Italy; Istituto Nanoscienze, CNR, 41125 Modena, Italy

[(g)] Faculty of Physics, Bielefeld University, D-33615 Bielefeld, Germany

[(h)] Institute of Nanotechnology (INT), Karlsruhe Institute of Technology (KIT), D-76131 Karlsruhe, Germany; Centre Européen de Sciences Quantiques (CESQ), Institut de Science et d'Ingénierie Supramoléculaires (ISIS), 67083 Strasbourg Cedex, France

## ABSTRACT

We report a highly symmetric {$Gd_9$} molecular nanocage (Panguluri et al., 2025). The magnetocaloric effect, evaluated by direct and indirect methods, exhibits a re-entrant shape in the isentropic curves, indicating a nontrivial evolution of magnetic entropy under applied fields. To elucidate this behavior, we used the finite-temperature Lanczos method on a model spin Hamiltonian. The calculations show that the antiferromagnetic exchange between $Gd^{3+}$ ions, together with the geometric frustration intrinsic to the {$Gd_9$} core, yields a degenerate ground state. An external field lifts this degeneracy, creating a regime with a sharply reduced density of states between 1.5 and 4 K, which drives the unconventional magnetocaloric response. The {$Gd_9$} cage thus represents a rare case of spin frustration from competing antiferromagnetic interactions, illustrating how frustrated topologies and tunable low-energy excitations can be exploited to modulate magnetothermal behavior.

**Keywords:** Cryogenics, Magnetism, Magnetocaloric effect, Spin-frustration, Gadolinium, Molecular magnet

**References:** Panguluri et al., J. Am. Chem. Soc. 2025, doi.org/10.1021/jacs.5c13048

# AN EFFICIENT APPROACH TO FABRICATE SPHERICAL MAGNETOCALORIC POWDERS

**Lukas Beyer**[*(a,b)], **Jens Freudenberger**[(a,b)], **Marc Straßheim**[(c,d)], **Tino Gottschall**[(c)], **Julia K. Hufenbach**[(a,b)]

[(a)]Leibniz Institute for Solid State and Materials Research Dresden (IFW Dresden), Helmholtzstr. 20, 01069 Dresden, Germany

[(b)] TU Bergakademie Freiberg, Gustav-Zeuner-Str. 5, 09599 Freiberg, Germany

[(c)]Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstr. 400, 01328 Dresden, Germany

[(d)] Technische Universität Dresden, Haeckelstr. 3, 01069 Dresden, Germany

*corresponding author: L.Beyer@ifw-dresden.de, +49 351 4659 685

## ABSTRACT

The application of magnetocaloric materials in heat exchangers is promising when spherical powders are utilized. Sphericity benefits the surface-to-volume ratio when using powders directly as regenerator beds, e.g. for hydrogen liquefaction, or when using them as feedstock for additive manufacturing. Powder beds are often preferred due to their simple handling and good compromise between heat exchange and pressure drop (Franco et al., 2018), (Wieland et al., 2020), (Tang et al., 2022). Typically, spherical powders are produced by gas atomization, a material and cost-intensive approach connected to greater amounts of excess. In contrast, the ultrasonic-based "*ATOLab+*" device by *3DLab* at Leibniz IFW Dresden allows for a more precise control and even small-scale fabrication. This helps selecting optimal compositions and parameters towards upscaling, while maintaining a low amount of material to start with (Hinrichs et al., 2021). We showcase the utilization of this device as an option in alloy development and present recent results on magnetic as well as computed tomographic characterization of spherical Gd- and LaFeSi-based powders (Straßheim et al., 2025).

**Keywords:** Magnetocaloric, Gadolinium, LaFeSi, Powder, Atomization

**References:**

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**Acknowledgement:** The authors acknowledge financial support from the transnational consortium M-ERA.NET for the project Cool BatMan: Battery Thermal Management System Based on High Power Density Digital Microfluidic Magnetocaloric Cooling (No. 9400). This project is co-financed with tax funds on the basis of the budget adopted by the Saxon state parliament. SAB-Nr: 100632843

# EXPLORING ANISOTROPIC MAGNETOCALORIC PERFORMANCE VIA FE/TI SUBSTITUTION IN NI–CO–MN–TI HEUSLER-TYPE MELT-SPUN RIBBONS

**Mariana Ríos[(a,b)], Patricia Lázpita[(a,b)], Joao H. Belo[(c)], Ricardo Pinto[(c)], Daniel Salazar[(a)]**

Basque Center for Materials, Applications, and Nanostructures - BCMaterials,
Leioa, 48940, Biscay, Spain. mariana.rios@bcmaterials.net
University of the Basque Country UPV/EHU, Electricity & Electronics Department,
Leioa, 48940 Bizcay, Spain
IFIMUP, Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, rua do Campo Alegre s/n, 4169-007 Porto, Portugal

## ABSTRACT

In this work, a series of $Ni_{35}Co_{13}Mn_{35}Fe_xTi_{17-x}$ (x = 0, 1, 2, 3) ribbons were prepared using the melt-spinning technique. Macroscopic magnetic measurements of the melt-spun ribbons show that the magnetostructural transformation strongly depends on the Fe/Ti ratio in the typically B2- ordered lattice, exhibiting a significant shift in the martensitic transformation (MT) temperature from 117 K to 318 K. Furthermore, these samples display a large change in magnetization (ΔM) during the MT, associated with the transition from the ferromagnetic austenite phase to the antiferromagnetic martensite phase, an appealing feature for magnetocaloric applications. Another remarkable observation is that the thermal hysteresis in this family of compounds remains nearly constant, around 25 K. The intriguing behavior of these melt-spun ribbons contributes to the growing understanding of all-d-metal Heusler-type systems and underscores their potential for anisotropic magnetocaloric technologies, particularly those requiring a broad operational temperature range, such as in aerospace applications.

**Keywords:** All-d Metal Heusler-type Alloys, Magnetocaloric effect MCE, Anisotropic magnetocaloric

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# FROM HYDROGEN TO HYDROGEN: TUNING THE PERFORMANCE OF GDFESI FOR MAGNETOCALORIC HYDROGEN LIQUEFACTION THROUGH HYDROGEN MODIFICATIONS

**Allan Döring[(a)], Wei Liu[(a)], Nene Teinor[(a)] Marc Strassheim[(b)], Tino Gotschall[(b)], Konstantin Skokov[(a)], Oliver Gutfleisch[(a)]**

[(a)] Institute of Materials Science, Technical University of Darmstadt Darmstadt, 64287, Germany, allan.doering@tu-darmstadt.de

[(b)] Dresden High Magnetic Field Laboratory (HLD-EMFL), Dresden, 01328, Germany, m.strassheim@hzdr.de

## ABSTRACT

Liquid hydrogen plays a major role in the shift towards a carbon-neutral energy society. Lowering the cost of its liquefaction is crucial for large-scale implementation, and magnetocaloric cooling presents a promising method to improve process efficiency. In this study, we tuned the transition temperature ($T_t$) of the R-T-X compound (GdFeSi) to produce a strong magnetocaloric effect within the hydrogen liquefaction range.

Hydrogen modification successfully reduced $T_t$ from 125 K to 25 K, aligning it with the desired temperature range. Furthermore, hydrogenation improved the isothermal entropy change, raising its peak from 10 to 35 $J{\cdot}kg^{-1}{\cdot}K^{-1}$ under a 10 T applied magnetic field. The directly measured adiabatic temperature change also increased, doubling from 6 to 12 K. These findings demonstrate that controlled hydrogenation is an effective strategy to adjust $T_t$ and enhance magnetocaloric performance of R-T-X compounds, offering a promising approach for advancing magnetocaloric hydrogen liquefaction technologies.

**Keywords:** Magnetocaloric, hydrogenation, hydrogen liquefaction

**References:**

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# SYSTEMATIC STUDY OF THE MICROSTRUCTURE AND MAGNETOCALORIC PROPERTIES IN OPTIMIZED $LAFE_{12}B_6$

**Protyasha Prachurja[(a)], Wei Liu[(a)], Alex Aubert[(a)], Benedikt Beckmann[(a)] Konstantin Skokov[(a)], Oliver Gutfleisch[(a)]**

[(a)] Institute of Materials Science, Technical University of Darmstadt Darmstadt, 64287, Germany,
protyasha.prachurja@tu-darmstadt.de

## ABSTRACT

Light rare-earth-based magnetocaloric (MC) materials are attractive due to their abundance and lower criticality concerns (Liu et al., 2023). Among them, $LaFe_{12}B_6$, a first-order MC compound, exhibits a phase transition near 36 K, making it a promising candidate for hydrogen liquefaction (Diop et al., 2016b). However, its strong MC effect appears only under high magnetic fields (>5 T), limiting low-field performance (Diop et al., 2016a). This reduced effect is attributed to its antiferromagnetic ground state and secondary phases in the microstructure. In this study, we systematically optimized the synthesis parameters—technique, composition, annealing temperature, and duration—to enhance phase purity and magnetocaloric response. We observed that annealing at 1383 K for 24 hours with a 3% La excess minimized the secondary phase from 13.2 to 7.7 wt.% and sharpened the first-order transition. As a result, the maximum magnetic entropy change increased markedly from −1 to −10 $Jkg^{-1}K^{-1}$ under a 5 T magnetic field.

**Keywords:** Magnetocaloric, La-Fe-B, hydrogen liquefaction, microstructure, first order phase transition material

**References:**

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# RESIDUAL FERROMAGNETIC REGIONS AFFECTING THE FIRST-ORDER PHASE TRANSITION IN FE-RH

**Alex Aubert[(a)], Konstantin Skokov[(a)], Benedikt Beckmann[(a)], Andrei Rogalev[(b)], Fabrice Wilhelm[(b)], Benedikt Eggert[(c)], Katharina Ollefs[(c)], Heiko Wende[(c)], Oliver Gutfleisch[(a)]**

[(a)]Functional Materials, Institute of Material Science, Technical University of Darmstadt, 64287 Darmstadt, Germany alex.aubert@tu-darmstadt.de

[(b)]European Synchrotron Radiation Facility, 38000 Grenoble, France

[(c)]Faculty of Physics and Center for Nanointegration Duisburg-Essen (CENIDE), University of Duisburg-Essen, 47057 Duisburg, Germany

## ABSTRACT

Among the magnetocaloric materials featuring first-order phase transitions (FOPT), FeRh is considered as a reference system to study the FOPT because it is a “simple” binary system with a CsCl structure exhibiting a large adiabatic temperature change. Ab initio predictions suggest that slight Fe/Rh stoichiometric changes strongly affect its FOPT, yet experimental verification remained limited. Here, we examine how small Fe excess influences the transition hysteresis. A 1 at.% Fe surplus induces a persistent ferromagnetic phase in ~10% of the sample, while 5 at.% fully suppresses the FOPT. Element-specific XMCD and Mössbauer spectroscopy reveal that this ferromagnetic signal arises from Fe antisite defects (Fe atoms occupying Rh (1b) sites) which create residual ferromagnetic domains. Consequently, even minor Fe enrichment drastically alters FOPT behavior and magnetocaloric performance. These findings clarify the origin of FeRh’s stoichiometric sensitivity and offer broader insight into FOPT dynamics in magnetocaloric materials.

**Keywords:** FeRh, first-order phase transition, ferromagnetic domains, XMCD, magnetocaloric

**References:** Aubert, A., Skokov, et al. 2024. Residual ferromagnetic regions affecting the first-order phase transition in off-stoichiometric Fe–Rh. ACS Applied Materials & Interfaces, 16(45), pp.62358-62370. https://pubs.acs.org/doi/10.1021/acsami.4c12432

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# IN-OPERANDO COMPARISON OF TAILORED FULL-HEUSLERS WITH FIRST- AND SECOND- ORDER TRANSITIONS FOR LOW-GRADE WASTE HEAT HARVESTING

**Eleonora Rusconi[a], Lorenzo Gallo[a], Simone Fabbrici[a], Giovanna Trevisi[a], Francesco Cugini[b], Massimo Solzi[b], Franca Albertini[a]**

[a] IMEM-CNR, Parma, 43124, Italy, eleonorarusconi@cnr.it, +39 0521 269230

[b] Department of mathematical, physical and computer sciences, University of Parma Parma, 43124, Italy

## ABSTRACT

Thermomagnetic energy harvesting shows potential for low-grade waste heat (T<100 °C) conversion to electricity by exploiting thermomagnetic materials showing, amongst others, a high magnetic jump (ΔM) at suitable temperatures (Dzekan et al., 2021). So far, first-order transition materials have been scarcely investigated. Here, two full- Heusler systems, $Ni_2MnGa$ and $Ni_2MnSn$ were respectively doped with copper (at Mn and Ga sites) (Endo et al., 2011), (Kataoka et al., 2010)and cobalt (at Ni sites) (Krenke et al., 2005), (Zhang et al., 2018)to obtain first-order, and second-order transitions within 300K and 400K. These were tested in a Curie wheel prototype (Cugini et al., 2025) to assess the impacts of transition type, transition temperature, and hysteresis width on the mechanical and electrical power outputs. Rotation was observed when the transition temperature was within the effective temperature gradient (ΔT) of the thermomagnetic wheel, even if hysteresis exceeded ΔT. Moreover, tailored doping yielded compositions with high ΔM and narrow hysteresis at suitable temperatures ($Ni_{49.4}Mn_{19.7}Cu_{6.5}Ga_{24.3}$ :30 $A/m^2kg$, hysteresis: 4±1 K; $Ni_{44.1}Co_{4.9}Mn_{39.1}Sn_{11.9}$: 74 $A/m^2kg$, hysteresis: 7±1 K).

**Keywords:** Heat4Energy, thermomagnetic harvesting, Heusler compounds, first order transitions

**References:**

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# COMPOSITION INFLUENCE AND MAXIMUM MAGNETOCALORIC EFFECT AT ROOM TEMPERATURE IN NI-CO-MN-TI ALL-D HEUSLER ALLOYS

**Benedikt Beckmann[(a)], Andreas Taubel[(a)], Tino Gottschall[(b)], Timo Niehoff[(b)] Konstantin Skokov[(a)], Oliver Gutfleisch[(a)]**

[(a)] Institute of Materials Science, Technical University of Darmstadt Darmstadt, 64287, Germany,
benedikt.beckmann@tu-darmstadt.de

[(b)] Dresden High Magnetic Field Laboratory (HLD-EMFL), Helmholtz-Zentrum Dresden-Rossendorf (HZDR)
Dresden, 01328, Germany

## ABSTRACT

Ni-Mn-based Heusler alloys, particularly Ni-Co-Mn-Ti, show large caloric effects driven by their martensitic transformation. Building on previous insights into the compositional influence on the transition entropy change, we optimized the alloy composition to evaluate the maximum magnetocaloric performance of this system near room temperature under high magnetic fields. The saturated magnetocaloric effect associated with the first-order magnetostructural transformation in $Ni_{37}Co_{13}Mn_{34.5}Ti_{15.5}$ was investigated using magnetometry, heat capacity, and direct adiabatic temperature change measurements in pulsed magnetic fields. A saturated isothermal entropy change of 38 $J(kgK)^{-1}$ and an adiabatic temperature change of –20 K were obtained, requiring magnetic fields of approximately 5–6 T in isothermal and 15 T in adiabatic conditions. Notably, this represents the highest directly measured adiabatic temperature change among magnetic field-induced first-order phase transitions at room temperature in recent years, providing fundamental insight into the upper performance limits achievable in magnetocaloric Heusler alloys under extreme magnetic field conditions.

**Keywords:** Magnetocaloric, Ni-Co-Mn-Ti, Heusler alloys

**References:**

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# CORRELATION OF MICROSTRUCTURE, POROSITY AND DEFECTS WITH $1^{ST}$-ORDER MAGNETOSTRUCTURAL TRANSITION CHARACTERISTICS IN NI–MN–SN HEUSLER ALLOY

**Johannes Puy[(a)], Enrico Bruder[(a)], Oliver Gutfleisch[(a)], Franziska Scheibel[(a)]**

[(a)] Institute of Materials Science, Technical University of Darmstadt Darmstadt, 64287, Germany,
johannes.puy@tu-darmstadt.de

## ABSTRACT

In this study, we examine the influence of particle size and microstructure on the nucleation and growth process of the temperature-induced first-order magnetostructural phase transition (FOMST) in Ni-Mn-Sn. Gas-atomized powders minimize the conflicting effects of morphology and defects. Magnetometry and in-situ microscopy reveal that reducing particle size from 150 µm to < 20 µm narrows transition temperature ranges to 1 K and increases thermal hysteresis to 30 K.

By adjusting the relative density in spark-plasma-sintered Ni-Mn-Sn, the effect of porosity on the FOMST is studied. Magnetometry reveals that an increase of the relative density from 77 % to 99 % narrows the transition ranges from 18 K to 9 K and decreases the transition temperature from 263 K to 254 K. In-situ microscopy reveals martensite nucleation at free particle surfaces in 77 % dense Ni-Mn-Sn, while nucleation in 99 % dense Ni-Mn-Sn arises at sintering necks.

**Keywords:** Magnetocaloric, Heusler alloy, Martensitic transformation, Microstructure, Nucleation, Spark-plasma-sintering

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# ON THE HIGH-FIELD CHARACTERIZATION OF MAGNETOCALORIC MATERIALS USING PULSED MAGNETIC FIELDS

**C. Salazar Mejia[(a)], T. Niehoff[(a, b)], M. Straßheim[(a, b)], E. Bykov[(a)], J. Wosnitza[(a,b)], T. Gottschall[(a)]**

[(a)] Dresden High Magnetic Field Laboratory (HLD-EMFL), Helmholtz-Zentrum Dresden-Rossendorf, Dresden 01328, Germany, c.salazar-mejia@hzdr.de

[(b)] Institut für Festkörper- und Materialphysik, TU Dresden, Dresden 01069, Germany

## ABSTRACT

Recent studies in materials and methods for hydrogen liquefaction and innovative techniques based on multicaloric materials have significantly broadened the scope of the field on magnetic refrigeration. The proper characterization of materials is now more crucial than ever. Specifically, at cryogenic temperatures and magnetic fields beyond permanent magnets. In this work, we give an overview of the characterization techniques established at the Dresden High Magnetic Field Laboratory using pulsed fields [1]. We discuss the advantages of the investigation method on the basis of well-studied magnetocaloric materials [2], including Laves phases [3] and rare-earths. Additionally, we show how the magnetic hysteresis plays a significant role at cryogenic temperatures and how its consequences are only measurable through direct measurements and, moreover, how indirect measurements could lead to wrong interpretation of the magnetocaloric effect at low temperatures.

**Keywords:** Magnetocaloric effect, direct measurements, hydrogen liquefaction, pulsed magnetic fields

**References:**

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# GIANT MAGNETOCALORIC EFFECT IN QUATERNARY FE–RH–IR–PD ALLOYS: EXPERIMENTAL AND THEORETICAL STUDY

**Vladimir Zverev[(a)], Radel Gimaev[(b)], Alexey Karpenkov[(c)], Gleb Zhezlyaev[(d)], Andrey Protasov[(d)], Denis Devyaterikov[(d)]**

[(a)]Faculty of Physics, M.V. Lomonosov Moscow State University, Leninskie Gori, Moscow, 119991, Russian Federation

[(b)]University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva 6, 1000 Ljubljana, Slovenia, radel.gimaev@fs.uni-lj.si, +38614771722

[(c)]Tver State University, Tver, 170100, Russian Federation

[(d)]M.N. Mikheev Institute of Metal Physics, Ural Branch, Russian Academy of Sciences, 18 S. Kovalevskoy St., Yekaterinburg, 620108, Russian Federation

## ABSTRACT

Binary Fe–Rh alloys exhibit significant magnetocaloric properties (Gimaev et al., 2020). However, their practically useful magnetocaloric effects (MCE) are limited to narrow composition and temperature ranges, and the maximum MCE in near-stoichiometric alloys occurs far from room temperature. Additionally, the high cost of rhodium restricts their applicability. Therefore, the search for alloys with giant MCE and reduced rhodium content is of great interest.

This study presents the first theoretical and experimental analysis of antiferromagnetic and ferromagnetic phase coexistence in quaternary bulk Fe–Rh–Ir–Pd alloys. First-principles calculations were conducted to determine electronic and magnetic properties. A giant MCE ($\Delta T_{ad}$ = 10.2 K at a magnetic field change of 1.8 T) was directly measured in the composition $Fe_{0.49}(Rh_{0.905}Pd_{0.06}Ir_{0.035})_{0.51}$.

Previously studied binary (Sánchez-Valdés et al., 2020) and ternary Pd-containing alloys (Jiménez et al., 2021) were used as references. Magnetic and structural properties were experimentally investigated, and the mechanisms underlying the observed giant MCE were analyzed.

**Keywords:** magnetocaloric, doped Fe-Rh alloys, direct measurements, first-principles calculations

**References:**

Gimaev, R.R., Vaulin, A.A., Gubkin, A.F. and Zverev, V.I. (2020). Peculiarities of Magnetic and Magnetocaloric Properties of Fe–Rh Alloys in the Range of Antiferromagnet–Ferromagnet Transition. The Physics of Metals and Metallography, 121(9), pp.823–850. doi:https://doi.org/10.1134/s0031918x20090045.

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# LIGHT-RARE-EARTH-BASED MAGNETOCALORIC COMPOUNDS: ADDRESSING CRITICALITY

**Marc Straßheim[a,b], Lukas Beyer[c,d], Timo Niehoff[a,b], Clara Estillac Silva[a,d], Catalina Salazar-Mejia[a], Tino Gottschall[a], Jochen Wosnitza[a,b]**

[a] Dresden High Magnetic Field Laboratory (HLD-EMFL), Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Dresden, 01328, Germany, m.strassheim@hzdr.de

[b] Institut für Festkörper- und Materialphysik, TU Dresden, Dresden, 01069, Germany

[c] Leibniz Institute for Solid State and Materials Research Dresden, Dresden, 01069, Germany

[d] TU Bergakademie Freiberg, Freiberg, 09599, Germany

## ABSTRACT

Laves-phase intermetallic compounds based on heavy rare-earth elements have long been recognized for their excellent magnetocaloric performance at low temperatures, making them promising candidates for cryogenic cooling applications (Liu et al., 2024), (Bykov et al., 2024), (Zhang et al., 2023). However, considering recent geopolitical developments, the reliance on heavy rare earths poses challenges in terms of cost, availability, and sustainability. In this work, we explore the magnetocaloric properties of Laves-phases formed from *light* rare-earth elements as an alternative, using hydrogenation to lower the transition temperature (Isnard et al., 2011). Using a combination of structural, magnetic, and direct adiabatic temperature change measurements at the Dresden High Field Laboratory, we demonstrate that these compounds exhibit notable magnetocaloric effects in the technologically relevant temperature range. The relationship between composition, magnetic ordering, and entropy change is analyzed to reveal how variations in the stoichiometry can influence magnetic transition behavior. Our findings highlight the potential of light-rare-earth Laves-phases as efficient and resource-conscious materials for next-generation solid-state cooling technologies.

**Keywords:** Magnetocaloric, laves-phases, light-rare-earths, hydrogenation, hydrogen liquefaction

**References:**

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# MAGNETIC AND MAGNETOCALORIC PROPERTIES OF GDRHIN INTERMETALLIC

**Sachin Gupta**

Department of Physics, Bennett University, Greater Noida 201310, India sachin.gupta@bennett.edu.in

## ABSTRACT

Rare-earth intermetallics exhibit rich magnetic behavior with promising functional properties (Pecharsky and Gschneidner, 1997), (Gupta and Suresh, 2015), (Gupta, 2023). This study investigates the structural, magnetic, and magnetocaloric properties of the GdRhIn compound. X-ray diffraction confirms a hexagonal crystal structure. Magnetization measurements reveal two successive transitions: an antiferromagnetic-to-ferromagnetic transition near 16 K and a ferromagnetic-to-paramagnetic transition around 34 K, corroborated by heat-capacity data. The isothermal magnetic entropy change ($\Delta S_m$) and refrigerant capacity (RC) are found to be 10.3 J $kg^{-1}$ $K^{-1}$ and 282 J $kg^{-1}$ for field changes of 70 kOe and 50 kOe, respectively (Kumar et al., 2024). The significant magnetocaloric effect suggests that GdRhIn is a potential candidate for low-temperature magnetic refrigeration.

**Keywords:** Magnetocaloric effect; magnetism; rare earths

**References:**

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# INTRAGRANULAR STRAIN SCANNING 3D XRD EXPERIMENTS ON THE FERROMAGNETIC PHASE TRANSITION IN $(MN,FE)_2(P,SI)$ MAGNETOCALORIC COMPOUNDS

**Øyvind Rørbakken[(a)], Hanggai[(a)], Haixing Fang[(b)], Francois Guillou[(c)], Niels van Dijk[(a)], Ekkes Brück[(a)]**

[(a)] Fundamental Aspects of Materials and Energy, TU Delft, 2629JB Delft, The Netherlands, o.rorbakken@tudelft.nl

[(b)] European Synchrotron Radiation Facility, Grenoble, 38000, France, haixing.fang@esrf.fr

[(c)] University of Caen Normandy, Caen, 14000, France, francois.guillou@unicaen.fr

## ABSTRACT

Among the magnetocaloric or thermomagnetic materials aimed at applications near ambient temperatures are those that undergo a first-order magnetic transition. Hexagonal $(Mn,Fe)_2(P,Si)$ compounds are often brittle, and show a significant change in the *c*/*a* ratio for the lattice parameters across the ferromagnetic (FM) -to- paramagnetic (PM) phase transition, leading to significant internal strains in cyclic magnetic field applications.

In high-energy synchrotron microbeam X-ray diffraction experiments we measured the characteristics of lattice parameters, grain orientations and intragranular strains in the FM and PM phases in single crystalline and polycrystalline $(Mn,Fe)_2(P,Si)$ samples using scanning 3D X-ray diffraction (s3DXRD). The ferromagnetic phase transition was induced by cooling and by applying a magnetic field. The local internal strain matrix was probed across the ferromagnetic transition in both the PM and FM phases.

**Keywords:** Magnetocaloric Material, First-Order Magnetic Transition, Synchrotron X-ray Diffraction

# NUMERICAL STUDY ON THE FREQUENCY DEPENDENCE OF THE DIRECT MAGNETOCALORIC EFFECT OF GADOLINIUM FILM

**Zhonghao Chang[a], Jorge Revuelta-Losada[a], Erika Fontana[b], Nora Dempsey[b], Katja Klinar[c], Andrej Kitanovski[c], Jia Yan Law[a], Victorino Franco[a]**

[a] Multidisciplinary Unit for Energy Science (MUFENS), Dpto. Física de la Materia Condensada, ICMS-CSIC, University of Seville, Seville, 41012, Spain. zchang@us.es (+34 675019988)

[b] Université Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, Grenoble, 38000, France

[c] Faculty of Mechanical Engineering, University of Ljubljana, Askerceva 6, Ljubljana 1000, Slovenia

## ABSTRACT

The magnetocaloric effect (MCE) is the adiabatic temperature change ($\Delta T_{ad}$) of a magnetic material under a varying magnetic field. Its utilization in magnetocaloric refrigerator presents a promising alternative to conventional vapor-compression systems. MCE is often evaluated indirectly through isothermal entropy change, but direct $\Delta T_{ad}$ measurements provide a practical performance metric, albeit influenced by the frequency of the field. Hence, we numerically investigate the frequency-dependent $\Delta T_{ad}$ in Gd films using a time-dependent, two-dimensional model of a custom experimental setup (Revuelta-Losada et al., 2025). The model couples heat transfer with MCE (Petersen et al., 2008) based on the Arrott-Noakes equation of state (Franco et al., 2008) for a 40 µm Gd film capped with 0.1 µm tantalum layer. The temperature response is found to saturate above a critical frequency, with the phase lag between excitation and response decreasing as frequency increases. The strong agreement between simulated and experimental data confirms the predictive capability of the model.

**Keywords:** Magnetocaloric effect; Heat transfer; Gd thin film; adiabatic temperature change; frequency

**References:**

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**Acknowledgement:** Work funded by the European Union under the Horizon Europe Program (project MolCal, Grant agreement ID: 101119865) and UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee (EPSRC EP/Y036565/1 and EP/Y036948/1). Additional funding from the European Innovation Council (project Magccine, Grant agreement 101161135), project PID2023-146047OB-I00 from AEI/10.13039/501100011033, and project PPIT2024-31833, (FEDER and Junta de Andalucía, and VII Plan Propio de Investigación from University of Seville).

# XCT IMAGE ANALYSIS FOR CHARACTERIZING 3D PRINTED THERMOMAGNETIC HEAT EXCHANGERS IN ENERGY HARVESTING APPLICATIONS

**Savvina Maria Papaioannou[a], Martinus Putra Widjaja[a], Bowei Huang[b], Michael Maschek[b], Diego Pineda Quijano[c], Niels van Dijk[c], Ekkes Brück[c], Anja Waske[a]**

[a]Bundesanstalt für Materialforschung und –prüfung (BAM), Berlin, 12205, Germany, anja.waske@bam.de

[b] Magneto B.V.,Delft, 2629 JD, The Netherlands, michael@magneto.systems, bowei@magneto.systems

[c] FAME group, Faculty of Applied Sciences, TU Delft, Delft, 2629 JB, The Netherlands, e.h.bruck@tudelft.nl, n.h.vandijk@tudelft.nl

## ABSTRACT

The 3D extrusion and post heat treatment process of the developed thermomagnetic heat exchanger blocks may introduce defects affecting heat transfer efficiency, magnetic and mechanical properties. This study investigates the morphology of these components and identify trends that enhance material performance in the demonstrator using the non-destructive characterization technique of X-ray computed tomography (XCT). XCT image analysis enables 3D visualization of the printed structures, while DragonFly software estimates scalar quantities such as volume, total surface area and void fraction. Image segmentation using Otsu's thresholding method, combined with morphological operations on the reconstructed XCT volume, facilitates estimation of the mean filament diameter, channel width, and internal porosity distribution along the building direction. The repeatability and dimensional accuracy of the printing process are assessed through slice analysis parallel and perpendicular to the water-flow direction. Finally, analysis of cycled heat exchangers reveals preliminary correlations between failure mechanisms and mechanical integrity of the blocks.

**Keywords:** X-ray computed tomography, Image analysis, Thermomagnetic, Heat exchangers.

**References:**

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# MICROMECHANICAL MODELING OF THE MARTENSITE TRANSFORMATION IN NIMNGA ALLOYS

**<u>Shibl Gill</u>[(a)], David Bohm[(a)], Anna Kosogor[(a)], Gilles A De Wijs[(b)], Ama Agyeman[(b)] Thomas Schrefl[(a)]**

[(a)] Department for Integrated Sensor Systems, University for Continuing Education Krems, Viktor Kaplan Straße 2E, 2700 Wiener Neustadt, Austria

[(b)] Radboud University, Institute for Molecules and Materials, Heyendaalseweg 135, 6525 AJ Nijmegen, The Netherlands

## ABSTRACT

The coupled magnetostructural transition from the paramagnetic cubic austenitic phase to the ferromagnetic tetragonal martensitic phase in NiMnGa alloys is central to magnetocaloric and thermomagnetic applications. We model eigenstresses and evaluate critical stresses in polycrystalline $Ni_{2\ x}MnGa_{1\ x}$ (x = 0.12) alloys using the finite element method (Xue et al., 2023), focusing on the martensitic transformation within grains. Our approach bridges scales by integrating DFT derived elasticity tensors and phonon dispersions with micrometer-scale finite element models of misoriented grains. We quantify eigenstresses arising from the martensite transformation, and demonstrate the influence of the microstructure: grain size, morphology, and orientation. Our results show that average grain size is proportional to eigenstress magnitudes, whereas the Von Mises Yield Criterion (VMYC) does not exhibit a direct correlation with grain size. Porosity dampens both eigenstresses and VMYC, highlighting its role in mechanical stability.

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**Keywords:** Microstructure, Finite Element Analysis, Martensite, Shape Memory Alloy

**References:** Xue, T.; Liao, S.; Gan, Z.; Park, C.; Xie, X.; Liu, W. K.; Cao, J. JAX-FEM: A Differentiable GPU-Accelerated 3D Finite Element Solver for Automatic Inverse Design and Mechanistic Data Science. Computer Physics Communications 2023, 291, 108802. https://doi.org/10.1016/j.cpc.2023.108802.

# FUNCTIONALLY GRADED $(MN,FE)_2(P,SI)$ THERMOMAGNETIC MATERIALS FOR ENERGY HARVESTING APPLICATIONS

**Suye Bu, Niels van Dijk, Ekkes Brück**

Fundamental Aspects of Materials and Energy, Delft University of Technology Delft, 2629 JB, the Netherlands,
S.Bu@tudelft.nl

## ABSTRACT

Thermomagnetic materials (TMMs) enable waste heat harvesting in thermomagnetic generators (TMGs) through temperature induced magnetization changes (ΔM), generating voltage via Faraday's law of induction. However, ΔM typically occurs within a narrow temperature span (10–30 K), limiting practical efficiency.

In this work, we investigate $(Mn,Fe)_2(P,Si)$ compounds as rare-earth-free TMM with tuneable properties. Composition optimization yields impurity-free (≥ 99%) and thermal hysteresis free (≤1 K) phases. By varying Mn and Si content, the Curie temperature ($T_C$) is tuned between 300–350 K precisely. Compositions with higher Mn exhibit large ΔM values, up to ~57.0 $A \cdot m^2 \cdot kg^{-1}$ within a 10 K range near $T_C$.

Furthermore, a functionally graded design is proposed by mixing materials with different $T_C$s and applying controlled heat treatments. Interdiffusion produces smooth compositional gradients that can be further engineered via additive manufacturing (e.g., 3D printing). The resulting $T_C$ gradient enhances heat exchange, sustains magnetic flux variation, and maximizes ΔM during TMG operation.

**Keywords:** Thermomagnetic generator, Thermomagnetic materials, $(Mn,Fe)_2(P,Si)$ compounds, Curie temperature gradient

**References:**

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# FIRST PRINCIPLES INVESTIGATION OF ELEMENTAL SUBSTITUTIONS AND H-LOADING IN $LA(FE_XSI_{1-X})_{13}$ – BASED MAGNETOCALORIC MATERIALS

**Anita Yadav[(a)]**, **Markus Gruner[(a)]**

[a)] Department of Physics and Center for Nanointegration (CENIDE), Universität Duisburg-Essen, Duisburg, 47057, e-mail: anita.yadav@uni-due.de

## ABSTRACT

$La(Fe_xSi_{1-x})_{13}$ is a leading magnetocaloric material, characterized by a sharp first-order phase transition and a large associated entropy change. Its behavior arises from an intricate coupling among the magnetic, electronic, and lattice degrees of freedom, which makes the material highly responsive to external factors and enables targeted tuning of its magnetocaloric response (Skokov et al., 2023), (Terwey et al., 2020), (Zhang et al., 2021). The operating range can be adjusted by substitution and interstitial loading of other elements, which alters the local atomic environment, redistributes electronic density, and interacts with Fe magnetic moments, thereby reshaping the interplay between structural and magnetic subsystems.

In this work, we apply first-principles calculations within the density-functional-theory framework to examine systematically, how chemical substitution and H-loading influences site occupancy and lattice expansion, and how these effects jointly dictate structural stability, spin interactions, and thermodynamic behavior. The results further provide a foundation for constructing machine-learning-based force fields, enabling efficient modeling of the thermodynamic properties of $La(Fe_xSi_{1-x})_{13}$ under hydrostatic and chemical pressure.

**Keywords:** Magnetocaloric materials, First-principles calculations

**References:**

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# Magnetocaloric & thermomagnetic devices

PB-24 Assessment of the thermodynamic performance evolution of a magnetic air-conditioner prototype
**Guilherme Fidelis Peixer** · *POLO — UFSC*

PB-25 Numerical modelling of an active magnetic regenerator based on the rotational magnetocaloric effect
**Radel Gimaev** · *FME, University of Ljubljana*

PB-26 Thermohydraulic study of gallium-based liquid metal in passive regenerators for magnetocaloric refrigeration
**Lamesgin Getnet** · *University of Twente*

PB-28 A miniature-scale multi-unit generator for low-grade waste heat recovery
**Maxim Wischnewski** · *Karlsruhe Institute of Technology*

PB-29 Design and performance results of a novel rotary thermomagnetic motor with a fin rotor for energy harvesting
**Clara Estillac Leal Silva** · *HZDR*

PB-30 Optimised fluid and heat management for increasing efficiency and frequency of thermomagnetic generators
**Ali Izadi** · *HZDR*

PB-31 From waste heat to energy harvesting: advancing Curie wheel performance through rotor design
**Lorenzo Gallo** · *IMEM-CNR*

PB-32 Performance analysis of magnetic refrigeration systems using nanofluids
**Luis David Misale** · *University of Genoa*

PB-50 FEMCE.multiphysics — a comprehensive tool for magnetic regenerator optimisation
**Henrique Souza** · *CICECO, Aveiro Institute of Materials*

# ASSESSMENT OF THE THERMODYNAMIC PERFORMANCE EVOLUTION OF A MAGNETIC AIR CONDITIONER PROTOTYPE

**Guilherme F. Peixer[(a)], Anderson Lorenzoni[(a)], Paulo Faria[(a)], Diego Reif[(b)], Alan D. Nakashima[(a)], Cristiano S. Teixeira[(b)], Jader R. Barbosa Jr.[(a,c)], Jaime A. Lozano[(a)]**

[(a)] POLO - Research Laboratories for Emerging Technologies in Cooling and Thermophysics, Department of Mechanical Engineering, Federal University of Santa Catarina (UFSC), Florianópolis, SC, 88040-900, Brazil,

guilherme.peixer@polo.ufsc.br

[(b)]Lab3M - Laboratory of Magnetism and Magnetic Materials, Department of Materials Engineering, Federal University of Santa Catarina (UFSC), Blumenau, SC, 89036-256, Brazil.

[(c)]Craft & Hawkins Department of Petroleum Engineering, Louisiana State University, Baton Rouge, LA 70803, United States.

## ABSTRACT

Heating, cooling, and air conditioning systems are responsible for about 8% of global greenhouse gas emissions and 20% of electricity use. With air-conditioning demand expected to triple by 2050, new sustainable technologies are urgently needed. Magnetocaloric refrigeration emerges as a promising solution. This study presents the design, optimization, and experimental evaluation of a pilot-scale magnetocaloric air conditioner. The system combines a rotor–stator magnetic circuit, $La(Fe,Mn,Si)_{13}H_z$ refrigerants, and tube-fin heat exchangers, optimized using Artificial Neural Networks and Genetic Algorithms (Peixer et al., 2023a). Three prototype generations were developed and improved based on experimental results. The first prototype achieved a temperature span suitable for air conditioning (22–35 °C) and a peak cooling power of 480 W (Peixer et al., 2023b). Remarkably, it is the only system reported to cool an actual room without using simulated thermal loads. The study demonstrates significant progress and outlines challenges toward large-scale implementation.

**Keywords:** Magnetocaloric Refrigeration, Air conditioning, Performance Evaluation.

**References:**

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# NUMERICAL MODELING OF AN ACTIVE MAGNETIC REGENERATOR BASED ON THE ROTATIONAL MAGNETOCALORIC EFFECT

**Radel Gimaev[(a)], Darja Gačnik[a)], Urban Tomc[(a)], Rafael Almeida[(b)], Rodrigo Kiefe[(c)], João H. Belo[(b)], João S. Amaral[(c)], Katja Klinar[(a)], Andrej Kitanovski[(a)*]**

[(a)]Faculty of Mechanical Engineering, University of Ljubljana, Askerceva 6, 1000 Ljubljana, Slovenia

[(b)]IFIMUP – Institute of Physics for Advanced Materials, Nanotechnology and Photonics, Department of Physics and Astronomy, Faculty of Sciences of University of Porto, Rua do Campo Alegre, 687, 4169-007 Porto, Portugal

[(c)]Physics Department and CICECO – Aveiro Institute of Materials, University of Aveiro, 3810-193 Aveiro, Portugal

, andrej.kitanovski@fs.uni-lj.si

## ABSTRACT

The rotational magnetocaloric effect (RMCE), based on magnetocrystalline anisotropy or demagnetizing effect, is promising approach for magnetic refrigeration. RMCE simplifies device design and improves compactness, as there is no need to vary the magnetic field. Moreover, RMCE enables operation at low fields: the adiabatic temperature change for 0.4 T (1.15 K) is 90% of that for 1 T (1.27 K) (R. Almeida et al., 2023).

To study RMCE-based active magnetic regenerators (AMRs), we developed a one-dimensional time-dependent numerical model. This model allows analysis of the dynamic operation under various parameters including fluid flow rate, operating frequency, field, AMR geometry and material properties. The performance parameters such as cooling power, coefficient of performance (COP), exergy efficiency are calculated.

The model was applied to optimize the RMCE-based AMR, determining optimal operating modes and design parameters through parametric analysis. Results provide design insights and support the development for RMCE-based prototypes.

**Keywords:** active magnetic regenerator, rotational magnetocaloric effect, heat transfer, refrigeration, magnetocaloric

**References:** Almeida, R., Freitas, S.C., Fernandes, C.R., R Kiefe, Araújo, J.P., Amaral, J.S., Ventura, J.O., Belo, J.H. and Silva, D.J. (2024). Rotating magnetocaloric effect in polycrystals—harnessing the demagnetizing effect. Journal of Physics Energy, 6(1), pp.015020–015020. doi:https://doi.org/10.1088/2515-7655/ad1c61.

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# THERMOHYDRAULIC STUDY OF GALLIUM-BASED LIQUID METAL IN PASSIVE REGENERATORS FOR MAGNETOCALORIC REFRIGERATION

**Lamesgin Getnet, Mina Shahi, Keerthivasan Rajamani**

University of Twente, Department of Thermal and Fluid Engineering, Thermal Conversion and Storage Group, Enschede, 7522 NB, Netherlands, l.a.getnet@utwente.nl

## ABSTRACT

Gallium-based liquid metals (GaLMs) present a significant opportunity for advancing magnetocaloric refrigeration (MR) due to their outstanding thermophysical properties. While theoretical models suggest GaLMs can enhance cooling capacity and coefficient of performance (COP)—potentially reducing system size and material costs compared to water-based counterparts (Kitanovski et al., 2016), (Rajamani et al., 2024), (Scarpa et al., 2023) - experimental validation is critically lacking. This study will provide a comprehensive experimental investigation into the thermohydraulics of GaLM flow in passive regenerators. Preliminary tests on stainless-steel parallel plate geometries have already indicated a 40% improvement in heat- transfer effectiveness over water at low frequencies. This work will expand upon these initial findings to systematically analyze pressure drop and heat transfer effectiveness in detail. The investigation will cover multiple regenerator geometries (e.g., parallel plate, circular, hexagonal, and rectangular channels) across a range of operating frequencies and utilization factors. The primary objective is to identify optimal regenerator designs for future integration into a full active magnetic regenerator (AMR) system. The results are intended to provide crucial experimental validation for GaLMs in AMR technology, paving the way for the development of higher-efficiency and lower-cost systems.

**Keywords:** Thermohydraulic, Liquid Metal, Passive Regenerator, Heat Transfer Effectiveness, Pressurre drop

**References:**

Kitanovski, A., Tušek, J., Tomc, U., Plaznik, U., Ožbolt, M. and Poredoš, A. (2016) Magnetocaloric Energy Conversion From Theory to Applications.

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# A MINIATURE SCALE MULTI-UNIT GENERATOR FOR LOW-GRADE WASTE HEAT RECOVERY

**Maxim Wischnewski[(a)], Makoto Ohtsuka[(b)], Hiroyuki Miki[(c)], Manfred Kohl[(a)]**

[(a)] Karlsruhe Institute of Technology (KIT)

Eggenstein-Leopoldshafen, 76344, Germany, maxim.wischnewski@kit.edu, +49 721 608-22767

[(b)] Tohoku University, Sendai, Japan

[(c)] Ishinomaki Senshu University, Ishinomaki, Japan

## ABSTRACT

Thermomagnetic materials like Ni-Mn-Ga exhibit a steep magnetization change near their Curie temperature allowing for waste-heat driven modulation of magnetic forces. Using this effect, we developed miniature-scale thermomagnetic generators (TMGs) that convert low-temperature waste heat at temperatures below 180 °C to electricity via resonant self-actuation of elastic cantilevers (Joseph et al., 2020). Recently, we extended this concept using a piezoelectric layer along the cantilever to increase the output voltage, facilitating power rectification (Wischnewski et al., 2024). Here we present the development of a TMG system consisting of five units operating simultaneously. Each unit, consisting of a piezoelectric TMG, a rectification and a storage circuit, is capable of generating up to 1.2 V DC at a source temperature of 110 °C. The units are connected in parallel to accumulate power output up to 0.2 µW. These results demonstrate the successful upscaling of TMGs consisting of parallel cantilevers operating in resonant self- actuation mode.

**Keywords:** Thermomagnetic generator, thermal energy harvesting, piezoelectric energy conversion, up-scaling, energy harvesting array, low-grade waste heat

**References:**

Joseph, J., Ohtsuka, M., Miki, H. and Kohl, M. (2020) ‘Upscaling of thermomagnetic generators based on Heusler alloy films’, *Joule*, 4, pp. 2718–2732. doi: 10.1016/j.joule.2020.10.019.

Wischnewski, M., Joseph, J., Ohtsuka, M., Miki, H. and Kohl, M. (2024) ‘A multilayer piezoelectric thermomagnetic film generator’, *Proceedings of the 2nd International Electronic Conference on Actuator Technology*, 4–6 November 2024, Basel, Switzerland: MDPI. Available at: sciforum.net/event/IECAT2024

# DESING AND PERFORMANCE RESULTS OF A NOVEL ROTARY THERMOMAGNETIC MOTOR WITH A FIN ROTOR FOR ENERGY HARVESTING

**Clara E. L. Silva[a,b], Dalila L. B. Torres[b], Marcos S. Tadim[b], Hugo C. C. Michel[b], Carmela M. P. Brraga[b], Marcelo A. Camara[b], Paulo V. Trevizoli[b]**

[a] Dresden High Magnetic Field Laboratory (HLD-EMFL), Helmholtz-Zentrum Dresden-Rossendorf Dresden, 01328, Germany, c.estillac-leal-silva@hzdr.de

[b]Universidade Federal de Minas Gerais, Belo Horizonte, 31270-901, Brazil, trevizoli@demec.ufmg.br

## ABSTRACT

Thermomagnetic motors are solid-state energy harvesters capable of converting low-temperature waste heat, inherent from industrial machinery and processes, into usable mechanical energy. In this presentation, we will disclose the design (Silva et al., 2025) and performance evaluation of a novel rotary thermomagnetic motor prototype, featuring a rotor with gadolinium fins and a stationary L-shaped permanent magnet circuit. Warm and cold fluid streams are supplied to specific regions of the rotor, generating motion by exploiting the force imbalance between the rotor's ferromagnetic and paramagnetic regions. Experimental tests measured torque and rotational speed under different operating conditions, enabling the construction of multiple torque and power output curves (Michel et al., 2025). The motor achieved maximum rotational speed of 348.5 RPM, peak output power of 4.67 W and holding torque of 2.3 Nm, surpassing the current state-of-the-art values (Takahashi et al., 2006), (Mehmood et al., 2021). These results demonstrate the potential of carefully designed thermomagnetic motors and suitable operating conditions to advance energy harvesting practical application.

**Keywords:** Energy Harvesting, Thermomagnetic Motors, Magnetic Circuit, Rotational Speed, Torque, Mechanical Power.

**References:**

Mehmood, M.U., Kim, Y., Ahmed, R., Lee, J. and Chun, W. (2021) *International Journal of Energy Research*. doi: 10.1002/er.6804.

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# OPTIMIZED FLUID AND HEAT MANAGEMENT FOR INCREASING EFFICIENCY AND FREQUENCY OF THERMOMAGNETIC GENERATORS

**Ali Izadi[(a)], Sebastian Fähler[(b)]**

[(a)] Helmholtz-Zentrum Dresden-Rossendorf, Dresden, 01325, Germany, A.izadi@hzdr.de

Faculty of Mechanical Science and Engineering, TUD Dresden University of Technology, Dresden, 01062, Germany

[(b)] Helmholtz-Zentrum Dresden-Rossendorf, Dresden, 01325, Germany, S.faehler@hzdr.de

## ABSTRACT

Low-grade waste heat is abundant but underutilized due to low performance of existing harvesting technologies (Kishore et al., 2018). Thermomagnetic Generators (TMG) are a promising technology, but still require increased efficiency and cycling frequency for higher output power.

Here we address both issues by Computational Fluid Dynamics (CFD) driven thermal/hydraulic networks coupled to magnetics. As starting point, we use a recent TMG design (Waske et al., 2019) and validated our digital-twin against it. Our improvements include novel fluid and heat management, which suppress hot–cold mixing, avoid backflow, remove temperature inhomogeneities over the thermomagnetic material, and prevent heat losses. These gains of the thermal subsystem have strong advantages for the magnetic subsystem, including lower magnetic stray fields, sharper magnetic flux change over time enabling higher frequencies. Compared to initial design we predict an order-of-magnitude increase in exergy efficiency and power density.

**Keywords:** Thermomagnetic Generator (TMG), Computational Fluid Dynamic (CFD), Low-grade waste heat, energy harvesting

**References:**

Kishore, R.A. and Priya, S. (2018) 'A review on design and performance of thermomagnetic devices', Renewable and Sustainable Energy Reviews, 81, pp. 33–44. doi: 10.1016/j.rser.2017.07.035.

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**Acknowledgement:** This project has received funding from the European Union under grant agreement No 101119852 Heat4Energy.

# FROM WASTE HEAT TO ENERGY HARVESTING: ADVANCING CURIE WHEEL PERFORMANCE THROUGH ROTOR DESIGN

**Lorenzo Gallo[(a)], Simone Fabbrici[(a)], Giovanni Garulli[(b)], Francesco Cugini[(a,b)], Jia Yan Law[(c)], Victorino Franco[(c)], Massimo Solzi[(a,b)], Franca Albertini[(a)]**

[(a)] Istituto IMEM-CNR, Parco Area delle Scienze 37/A, 43124, Parma, Italy, lorenzogallo@cnr.it

[(b)] Dipartimento di Fisica, Università di Parma, Parco Area delle Scienze 7/A, 43124 Parma, Italy

[(c)] Departamento de Física de la Materia Condensada, ICMS-CSIC, Universidad de Sevilla, Sevilla 41080, Spain

## ABSTRACT

This study aims to evaluate how rotor architecture influences thermomagnetic (TM) energy conversion efficiency in Curie-wheel-type generators. TM generation enables the transformation of low-grade waste heat into mechanical or electrical energy via temperature-induced magnetization changes in a magnetic field gradient (D. Dzekan et al., 2021). A laboratory-scale TM generator (F. Cugini et al., 2025) was used to test three $Ni_{48}Mn_{36}In_{16}$- based rotors: (i) an epoxy composite with 87 wt% powder; (ii) a 3D-printed composite with reduced thickness to enhance surface-to-volume ratio; and (iii) a polymer-free metallic rotor produced by suction casting. In-operando measurements under controlled thermal gradients (297–340 K) revealed that power output and rotation dynamics are strongly affected by heat exchange efficiency. The optimized configurations achieved some of the highest power outputs reported for Curie-wheel systems. These findings highlight rotor geometry and interfacial design as critical levers for improving TM conversion, offering valuable insights for the development of next-generation waste heat recovery technologies.

**Keywords:** Thermomagnetic energy conversion; Curie-wheel generator; NiMn-based Heusler compounds; Heat exchange efficiency

**References:**

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**Acknowledgement:** This Project was partially funded by European Union – NextGenerationEU under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.1 - Call for tender No. 1409 of 14–09–2022 of Italian Ministry of University and Research (Project Code P2022KMXBL, Concession Decree No. 0001381 of 01/09/2023 adopted by the Italian Ministry of Universities and Research, CUP D53D23019360001, “Small-scale Thermomagnetic Energy harvesters: from materials to devices”).

# PERFORMANCE ANALYSIS OF MAGNETIC REFRIGERATION SYSTEMS USING NANOFLUIDS

**Luis David Misale[a], Federico Scarpa[a], J.A. Bocanegra[b]**

[a] DIME - Department of Mechanical, Energy, Management and Transportation Engineering, University of Genoa, Via All'Opera Pia 15a, 16145, Genoa, Italy luisdavid.misale@edu.unige.it

[b] DIME - Department of Mechanical, Energy, Management and Transportation Engineering, University of Genoa, Via All'Opera Pia 15a, 16145, Genoa, Italy

augusto.bocanegra@unige.it

## ABSTRACT

The efficiency of magnetic refrigeration systems, a sustainable alternative to conventional cooling technologies, depends heavily on the heat transfer fluid (Scarpa et al., 2024). This work analyzes an active magnetic regenerator that uses a 30% mass mixture of water and propylene glycol, subsequently enriched with various nanoparticles ($Al_2O_3$, CuO, fused-$SiO_2$, $TiO_2$, α-$SiO_2$, ZnO, SiC). The thermophysical properties of the nanofluids were determined using empirical correlations, and their impact on system performance was evaluated using a dedicated model. The results show that volumetric concentration and particle size are the key parameters: an increase in concentration and a reduction in particle size significantly improve cooling capacity, albeit with a reduction in the coefficient of performance. The material of the nanoparticles, on the other hand, has a relatively minor influence on overall thermal performance. These conclusions provide useful insights for optimizing nanofluids in magnetic refrigeration.

**Keywords:** Magnetic refrigeration; Active magnetic regenerator; Nanofluids; Cooling power; Coefficient of Performance; Nanoparticle

**References:** Scarpa, F., Bocanegra, J.A., Fanghella, P. and Tagliafico, L.A. (2024) 'Improving the performance of room temperature rotary magnetic refrigerators via magnet shape optimization', International Journal of Refrigeration, 164, pp. 12–28. doi:10.1016/j.ijrefrig.2024.04.022.

# FEMCE.MULTIPHYSICS – A COMPREHENSIVE TOOL FOR MAGNETIC REGENERATOR OPTIMIZATION

**Henrique Souza**[(a)], **Rodrigo Kiefe**[(a)], **João Amaral**[(a)]

[(a)] Department of Physics and CICECO – Aveiro Institute of Materials, 3810-193, Aveiro, Portugal,
hberganton@ua.pt

## ABSTRACT

The optimization of magnetic regenerators is critical for the improvement of the performance of magnetic refrigeration. FEMCE (Kiefe and Amaral, 2025) was created to facilitate this process by simulating the non-linear magnetostatics problem for an arbitrary refrigerant of an arbitrary magnetic material, determining the Magnetocaloric Effect (MCE), as well as the demagnetizing field-induced Rotating Magnetocaloric Effect (dRMCE). This work extends the capability of FEMCE to calculate other important quantities, namely the magnetic work and force/torque required to (de)magnetize the refrigerant; the pressure drop of the passing fluid; and the time it takes for the heat to transfer to the fluid and after an adiabatic (de)magnetization. This software, which was named FEMCE.multiphysics, is publicly available on GitHub (de Souza, 2025).

**Keywords:** finite-element method; multiphysics; magnetocaloric effect; fluid flow; heat transfer; refrigeration

**References:**

Kiefe, R., and Amaral, J.S. (2025) ‘FEMCE – A 3D finite element simulation tool for magnetic refrigerants’, Int. J. Refrig., 173, p180-184. https://doi.org/10.1016/j.ijrefrig.2025.02.017

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# Mechanocaloric or thermomechanical devices

PB-34 Numerical optimisation of irreversible Brayton barocaloric refrigeration cycle using $(C_{10}H_{21}NH_3)_2MnCl_4$
**Pravinth Balthazar** · *UTS, Sydney*

PB-35 Shell-based finite element modelling for optimisation of buckling stability of superelastic SMA structures
**Adam Plantarič** · *FME, University of Ljubljana*

PB-36 Universal elastocaloric test environment: design considerations and challenges
**Rawan Barakat** · *Saarland University*

PB-37 Performance-driven design of an elastocaloric regenerator: a numerical investigation
**Luca Cirillo** · *Univ. degli Studi di Napoli Federico II*

PB-38 Multi-objective optimisation for the development of an elastocaloric cooling device
**Luca Cirillo** · *Univ. degli Studi di Napoli Federico II*

PB-39 SMArtCool — development and validation of a translatory elastocaloric system
**Philipp Molitor** · *Saarland University c/o ZeMA*

PB-40 A custom high-pressure calorimeter to evaluate the barocaloric effect
**Emmanouil Charkiolakis** · *INMA-CSIC, UniZar*

PB-41 An energy-efficient actuator based on work recovery in elastocaloric cooling
**Jiyuan Hu** · *Hong Kong University of Science and Technology*

PB-42 Stamping & stacking: an efficient approach to manufacture refrigerant for compressive elastocaloric cooling
**Changfeng Su** · *HKUST*

PB-43 A reliable elastocaloric regenerator based on fatigue-resistant shape memory alloy
**Yang Li** · *HKUST*

# NUMERICAL OPTIMISATION OF IRREVERSIBLE BRAYTON BAROCALORIC REFIRGERATION CYCLE USING $(C_{10}H_{21}NH_3)_2MNCL_4$

**Pravinth Balthazar[(a)], Mohammad S. Islam[(a)], Nick S. Bennett[(a)]**

[(a)] School of Mechanical and Mechatronic Engineering, University of Technology Sydney Ultimo, NSW 2007, Australia, Pravinth.Balthazar@uts.edu.au

## ABSTRACT

Barocaloric cooling, which employs solid-state refrigerants, is gaining significant attention (Cirillo et al., 2022; Kitanovski et al., 2015; Lloveras and Tamarit, 2021). $(DA)_2MnCl_4$ (DA - decyl ammonium, $C_{10}H_{21}NH_3$) is a promising refrigerant due to ultra-low hysteresis temperature and low operational pressure (Li et al., 2021; Seo et al., 2022). However, numerical analyses of Barocaloric refrigeration cycles remain limited. This study analyses $(DA)_2MnCl_4$ using an irreversible Brayton refrigeration cycle. It optimises the *COP*, cooling temperature span, and Dimensionless Refrigeration Capacity (*DRC*) by evaluating the irreversibility factor, timing ratio, and heat reservoir temperatures at 50 MPa. The results show that an irreversibility factor ($\eta$) $\geq$ 0.86 is required to utilise the phase-transition region fully. Reducing the timing ratio by 25% (from 1.0) at $\eta$ = 0.95 increases the COP from 1.9 to 6.7 and the DRC from 3.0 to 3.4 at a heat source temperature of 313.7 K and a heat sink of 314.6 K. This study confirms the feasibility of $(DA)_2MnCl_4$, with future work focusing on cascade-cycle and integrated heat exchangers to optimise performance for device development.

**Keywords:** Timing ratio, irreversibility, Cooling Temperature Span, COP, Dimensionless Refrigeration Capacity

**References:**

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# SHELL-BASED FINITE ELEMENT MODELLING FOR OPTIMIZATION OF BUCKLING STABILITY OF SUPERELASTIC SMA STRUCTURES

**Adam Plantarič[(a)], Luka Porenta[(a)], Jaka Tušek[(a)], Miha Brojan[(a)]**

[(a)] Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva 6, 1000 Ljubljana, Slovenia,
telephone: +386 04 143 117
e-mail: adam.plantaric@fs.uni-lj.si

## ABSTRACT

Superelastic shape memory alloys (SMAs) demonstrate exceptional fatigue resistance under compressive loading, making them highly suitable for practical applications like elastocaloric cooling. To enhance heat transfer and ensure efficient device performance, elastocaloric systems often rely on thin-walled components, which are prone to buckling and structural collapse under compression. To accurately predict this buckling behavior, shell finite element models combined with SMA constitutive laws can be employed. In this work, we present a numerical approach to predict and assess the buckling performance of thin-walled SMA structures. This method enables geometric optimization aimed at minimizing or completely eliminating buckling. We further explore and discuss the buckling stability and geometric optimization of various configurations - such as corrugated cylinders, sheets, and spiral geometries - designed for use as elastocaloric structures in active elastocaloric regenerators.

**Keywords:** shape memory alloys, elastocaloric, shell buckling, geometrical optimization, corrugated geometry

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# UNIVERSAL ELASTOCALORIC TEST ENVIRONMENT: DESIGN CONSIDERATIONS AND CHALLENGES

**Rawan Barakat[(a)], Felix Welsch[(a)], Paul Motzki[(a)(b)]**

[(a)]Saarland University, Department of Systems Engineering Saarbruecken, 66123, Germany,
rawan.barakat@uni-saarland.de

[(b)] Center for Mechatronics and Automation Technology (ZeMA gGmbH), Saarbruecken, 66121, Germany

## ABSTRACT

In recent years, numerous continuously operating cooling machines based on the efficient and environmentally friendly emerging technology of Elastocalorics (EC) have been developed. These machines utilize different operation concepts and target improvements in Coefficient of Performance (COP), cooling power, or temperature span (ΔT). To enable a reliable comparison of different machines' performance and to define the current state of the technology within the broader context of cooling technologies, standardized measurement approaches are necessary.

Therefore, the EU-funded project SMACool aims to establish the foundation for standards and testing methodologies for elastocaloric machines, especially in HVAC applications, and to develop a universal elastocaloric test environment. This environment is designed to be adaptable to various EC-Machine configurations, in terms of size, geometry, thermal power, and heat exchange medium. This work presents the final design of the test environment, discussing the design considerations, key challenges, and planned testing methods.

**Keywords:** Elastocalorics, EC-machines, performance evaluation, standardized measurement, HVAC

**References:**

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**Acknowledgement:** SMACool is an EU-funded project that has received funding from the European Union's Horizon Europe 2023-PATHFINDERCHALLENGES-01 program under Grant Agreement N. 101162223

# PERFORMANCE-DRIVEN DESIGN OF AN ELASTOCALORIC REGENERATOR: A NUMERICAL INVESTIGATION

**Luca Cirillo[(a)], Sabrina Gargiulo[(a)], Adriana Greco[(a)], Claudia Masselli[(a)]**

[(a)] Department of Industrial Engineering, University of Naples Federico II, P.le Tecchio 80, 80125 Naples Italy, * Corresponding author e-mail: sabrina.gargiulo@unina.it

## ABSTRACT

Within the framework of the SMACOOL project, the use of a spiral-shaped elastocaloric regenerator is investigated. The proposed design consists of NiTi elastocaloric material under compression, alternated with water flow channels acting as the heat-transfer medium (Tušek *et al.*, 2016; Cirillo *et al.*, 2026). A detailed numerical analysis was carried out to evaluate the energetic performance of the regenerator at a fixed operating frequency of 1 Hz, while varying the thickness of both the water channels and the NiTi layers in the range of [0.20 ;0.50] mm. Results show the $\Delta T_{cold}$ and the $Q_{cold}$ as a function of volume ratio. However, configurations with increased water channels exhibit higher cooling power, attributed to the greater mass flow rate of the fluid, but a lower temperature variation. This work provides insights into the geometric optimization of elastocaloric regenerator through the study of thermal performance in term of temperature variation and cooling power.

**Keywords:** Elastocaloric regenerator, solid state refrigeration, geometry optimization, numerical analysis, Finite Element Method.

**References:**

Cirillo, L. et al. (2026) "Numerical simulations for regenerator optimization in an experimental elastocaloric cooling prototype based on shape memory alloys," Energy Conversion and Management, 348, p. 120616. Available at: https://doi.org/10.1016/J.ENCONMAN.2025.120616.

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**Acknowledgement:** The study is realized whitin the project SMACOOL that is financially supported by EIC Pathfinder Challenge 2023 – Clean Efficient Cooling

# MULTI-OBJECTIVE OPTIMIZATION FOR THE DEVELOPMENT OF AN ELASTOCALORIC COOLING DEVICE

**Luca Cirillo[(a)], Adriana Greco[(a)], Claudia Masselli[(a)], Vincenzo Orabona[(a)*]**

[(a)] Department of Industrial Engineering, University of Naples Federico II P.le Tecchio 80, 80125 Naples Italy City, * corresponding author e-mail: vincenzo.orabona2@unina.it

## ABSTRACT

Elastocaloric refrigeration is a promising solid-state alternative to conventional cooling technologies(Mevada *et al.*, 2024). This study presents a multiobjective optimization of the energy performance of an elastocaloric cooling device (Cirillo *et al.*, 2026), aiming to maximize the cold-side temperature difference ($\Delta T_{cold}$) and the cooling power ($Q_c$). Due to high computational costs, CFD simulation results for a spiral-shaped AeR regenerator— varying water channel thickness, NiTi thickness, mechanical load time, heat transfer fluid residence time, and fluid velocity—are used to train a surrogate model, which then serves as the fitness function for a genetic algorithm. This algorithm explores extended input ranges to identify optimal solutions along the Pareto front of $\Delta T_{cold}$ versus $Q_c$. The proposed approach captures trade-offs between competing performance indicators and provides guidelines for the optimal design of the device architecture, supporting the selection of input parameters for enhanced energy performance.

**Keywords:** elastocaloric device, numerical analysis, multi-objective optimization, genetic algorithm

**References:**

Cirillo, L. et al. (2026) “Numerical simulations for regenerator optimization in an experimental elastocaloric cooling prototype based on shape memory alloys,” Energy Conversion and Management, 348. Available at: https://doi.org/10.1016/j.enconman.2025.120616.

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**Acknowledgement:** The study is carried out as part of the SMACOOL project, which receives financial support from the EIC Pathfinder Challenge 2023.

# SMARTCOOL – DEVELOPMENT AND VALIDATION OF A TRANSLATORY ELASTOCALORIC SYSTEM

**Lukas Ehl[(a)(b)], David Zimmermann[(a)(b)], Franziska Louia[(b)], Stefan Seelecke[(b)], Paul Motzki[(a)(b)]**

[(a)] Center for Mechatronics and Automation Technology (ZeMA gGmbH),
Saarbruecken, 66121, Germany, lukas.ehl@uni-saarland.de

[(b)] Saarland University, Department of Systems Engineering Saarbruecken, 66123, Germany

## ABSTRACT

Elastocaloric cooling, based on reversible stress-induced phase transitions in shape memory alloys, offers a sustainable alternative to vapor-compression systems without harmful refrigerants. This solid-state technology achieves high efficiency and energy density, providing temperature spans over 20 K and high theoretical efficiency, while drastically lowering environmental impact. However, challenges such as mechanical fatigue, system efficiency, and cost-effective material processing remain unsolved for large-scale use. In automotive electrification, elastocaloric systems offer potential for battery and cabin thermal management with higher efficiency and reduced energy consumption.

Research remains essential in cyclic stability, system design, and scalable manufacturing. Within the publicly funded project SMArtCool, a translation-based system architecture is being developed to exploit these effects efficiently. A dedicated test rig investigates key components and system parameters to guide design optimization. The setup and first experimental results will be presented at Thermag XI 2026, highlighting progress toward automotive integration.

**Keywords:** Elastocalorics, Validation, System design, Energy recuperation

**References:**

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**Acknowledgement:** SMArtCool is a project that has received funding from the Federal Ministry for Economic Affairs and Energy under Grant Agreement N. 03EN2123C.

# A CUSTOM HIGH-PRESSURE CALORIMETER TO EVALUATE THE BAROCALORIC EFFECT

**Emmanouil K. Charkiolakis[(a)], David Gracia[(a)], Marc Ubach I Cervera[(a)], Carlos Cosculluela[(a)], Pedro Téllez[(b)], Vera Cuartero[(a)], Javier Blasco[(a)], Gloria Subías[(a)], Marco Evangelisti[(a)]**

[(a)]Instituto de Nanociencia y Materiales de Aragón (INMA), CSIC, Universidad de Zaragoza Zaragoza, 50009, Spain, e-mail charkiolakis@unizar.es

[(b)]Servicio General de Apoyo a la Investigación (SAI), Universidad de Zaragoza, Zaragoza, 50009, Spain

## ABSTRACT

To evaluate the barocaloric effect, we havedeveloped a customcalorimetric setup based on a piston-cylinder CuBe high-pressure cell (Gracia et al., 2025). A surface-mount device (SMD) resistor serves simultaneously as sample-holder and pressure sensor, while Daphne oil 7373 is used as the hydrostatic pressure-transmitting medium. The system can be operated either with a liquid-nitrogen-based cryostat (Oxford Instruments OptistatDN) or a compact Stirling cryocooler (RIGID RS100 Pro), both covering a temperature range from approximately 80 K to 400 K. The temperature dependence of the isobaric heat capacity at various pressures up to 20 kbar is determined by continuously monitoring the sample temperature with a K-type thermocouple in direct contact with it, complemented by a Pt100 sensor outside the pressure cell. Data are collected during both heating and cooling cycles. From these measurements, the barocaloric figures of merit (D$S_T$ and D$T$) are indirectly estimated using standard thermodynamic formulations. Preliminary results on the direct measurement of D$T$ will also be presented.

**Keywords:** Barocaloric Effect, High-pressure calorimetry, Custom-build Setup

**References:** D. Gracia, V. Cuartero, C. Popescu, A. Trapali, T. Mallah, M.-L. Boillot, J. Blasco, G. Subías, M. Evangelisti, J. Mater. Chem. A 13, 17944 (2025).

**Acknowledgement**: This work has received support from EU (MSCA-DN MolCal, 101119865) and ERDF/EU (PID2021- 124734OB-C21, CEX2023-001286-S).

# AN ENERGY-EFFICIENT ACTUATOR BASED ON WORK RECOVERY IN ELASTOCALORIC COOLING

**Jiyuan Hu[(a)], Qingping Sun[(a)]**

Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Kowloon, Hong Kong, 999077, China, meqpsun@ust.hk (Q. Sun)

## ABSTRACT

Elastocaloric cooling has garnered significant research interest as a promising alternative to traditional vapor-compression refrigeration. However, the energy efficiency of current elastocaloric cooling devices is limited by the unrecovered work of the loaded material. In this work, we propose a work recovery strategy for enhancing the efficiency of elastocaloric cooling and develop an actuator for inducing phase transitions in shape memory alloys (SMA) efficiently. Two compression-based SMA regenerators are connected by transmission mechanisms and driven by a motor. Through this unique transmission mechanism, the strain energy of one loaded SMA regenerator can be directly transferred to another regenerator, reducing its required work for loading in next cycle. Ideally, the motor would only input the work to overcome the hysteresis loss of SMA in a frictionless system. In the actual operation, our actuator achieves a 2-fold reduction in the required work when driving a linear elastic material, compared to driving the material individually without work recovery. Low required driving power can further enhance the coefficient of performance (*COP*) in the elastocaloric cooling devices. These results show the potential to improve the energy efficiency of the elastocaloric cooling device and promote the commercialization of this cooling technology.

**Keywords**: Elastocaloric, COP, Work recovery, Energy Efficiency.

# STAMPING & STACKING: AN EFFICIENT APPROACH TO MANUFACTURE REFRIGERANT FOR COMPRESSIVE ELASTOCALORIC COOLING

**Changfeng Su[a], Qingping Sun[a]**

[a]Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Kowloon, Hong Kong, 999077, China, meqpsun@ust.hk (Q. Sun)

## ABSTRACT

Elastocaloric cooling using shape memory alloy (SMA) is a promising substitute for conventional vapor-compression refrigeration. Compression-based elastocaloric prototypes utilize tubular refrigerants with different cross-section geometry processed by wire electric discharge machining (WEDM) to achieve large specific heat transfer area as well as high mechanical stability. However, the expensive and time-consuming WEDM method hinders commercialization of elastocaloric cooling. Here, we propose an approach based on stamping and stacking of NiTi thin films to manufacture refrigerant with multi-cell cross-sectional geometry for compressive elastocaloric cooling. We stamp and cut the NiTi thin films into pieces with micro holes, then stack thousands of pieces for compression. The geometric parameters of the multi-cell cross-section are optimized by numerical simulation. Compared with tubular structure processed by WEDM, our refrigerant processed by stamping & stacking demonstrates ultrahigh fatigue life. Stamping & Stacking is a faster (up to hundreds of pieces per minute) and cheaper way to process refrigerant with large specific heat transfer area and high structural stability, making elastocaloric cooling technique more affordable for practical applications.

**Keywords:** Shape memory alloy, Elastocaloric cooling, Bending, Energy Efficiency, Dehumidification

# A RELIABLE ELASTOCALORIC REGENERATOR BASED ON FATIGUE-RESISTANT SHAPE MEMORY ALLOY

**Yang Li[(a)], Qingping Sun[(a)]**

[(a)] Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Kowloon, Hong Kong, 999077, China, meqpsun@ust.hk (Q. Sun)

## ABSTRACT

Conventional refrigeration based on vapor-compression technology has been used and developed for over a century, accompanied by high global warming-potential refrigerant emissions. For the carbon-neutral goal, elastocaloric cooling is a promising solution to achieve highly efficient and environmentally friendly refrigeration without direct greenhouse gas emissions. However, the current elastocaloric devices cannot meet practical needs, which require a constant cooling performance in long-term operation. Here, we developed a compact compression-based regenerator using TiNiCuCo SMA tubes with multilayer fin-type cross-section. The single SMA tube is only 20mm long to prevent buckling and extend the structural fatigue life. Then, a long series of connected SMA tubes ensures a large temperature span and cooling power. Due to the lower phase transition stress of TiNiCuCo SMA, more refrigerants can be driven in a regenerator, where the multilayer fin-type structure increases material utilization with a competent specific heat transfer area. Compared with binary nickel titanium, using TiNiCuCo material eliminates the functional fatigue of the regenerator. Finally, the regenerator achieves 400W cooling power without degradation. No structural fatigue was found during the operation. These results show the elastocaloric regenerator has excellent potential to convert to commercial applications such as air conditioners and industrial chillers.

**Keywords:** Elastocaloric, Compression, Cooling power, TiNiCuCo.

*POSTER PRESENTATION*

# Mechanocaloric & thermomechanical materials

PB-44 Barocaloric effect in Fe(4-atz)$BF_4$ spin-crossover complex
**Süheyla Yüce** · *Ondokuz Mayıs University*

PB-45 Fatigue crack growth modelling of elastocaloric materials
**Tim Grupp** · *Saarland University*

PB-46 Tuning transformation temperatures in Cu–Al–Mn shape-memory alloys through Sn addition for elastocaloric cooling
**Lovro Cigić** · *UL, Fac. Natural Sciences & Engineering*

PB-47 Advancing barocaloric refrigeration through enhanced thermal and mechanical performance of spin crossover materials
**Aya Benjira** · *GREMAN UMR7347, France*

# BAROCALORIC EFFECT IN FE(4ATZ)$BF_4$ SPIN CROSSOVER COMPLEX

**Suheyla Yüce[a,b], Kubra Gurpinar[c], Melony Dilshad[b], Eyüp Kavak[d], Giulio Lampronti[b], Orhan Atakol[c], Lluís Mañosa[e], Baris Emre[d,b], Xavier Moya[b]**

[a]Department of Physics, Faculty of Science, Ondokuz Mayis University,
Samsun, 55139, Türkiye, syuce@omu.edu.tr

[b]Department of Materials Science, University of Cambridge, Cambridge CB3 0FS, UK,

[c]Department of Chemistry, Faculty of Science, Ankara University, Ankara, 06100, Türkiye.

[d]Department of Engineering Physics, Faculty of Engineering, Ankara University, Ankara, 06100, Türkiye,

[e] Departament de Fisica de la Matèria Condensada, Facultat de Fisica, Universitat de Barcelona, Barcelona, 08028, Catalonia.,

## ABSTRACT

Spin crossover (SCO) materials, characterized by their reversible transition between low-spin and high-spin electronic states, have recently emerged as promising candidates for solid-state cooling applications based on barocaloric effects (Romanini et al., 2021), (Vallone et al., 2019). The spin transition can be triggered not only by temperature but also by external pressure, resulting in substantial entropy and volume changes that can be harnessed for efficient barocaloric cooling. This pressure-induced spin transition is often accompanied by a large barocaloric effect, comparable to or even exceeding that of conventional caloric materials. In particular, Fe(II)-based coordination compounds have demonstrated remarkable barocaloric strengths near room temperature, owing to their tunable ligand fields and structural flexibility. The magnitude and reversibility of the barocaloric response depend strongly on the cooperativity of the spin transition, lattice compressibility, and hysteresis behavior. In this work, we report the potential of SCO compounds (Fe(4atz)$BF_4$) as efficient, environmentally friendly solid-state refrigerants operating near ambient conditions.

**Keywords:** Barocaloric, spin crossover, solid-state cooling

**References:**

Romanini, M., Wang, Y., Gürpinar, K., Ornelas, G., Lloveras, P., Zhang, Y., Zheng, W., Barrio, M., Aznar, A., Gràcia-Condal, A. and Emre, B. (2021) 'Giant and reversible barocaloric effect in trinuclear spin-crossover complex Fe3(bntrz)6(tcnset)6', Advanced Materials, 33(10), article 2008076. doi: 10.1002/adma.202008076.

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# FATIGUE CRACK GROWTH MODELING OF ELASTOCALORIC MATERIALS

**Tim Grupp[a], Franziska Louia[a], Paul Motzki[a][b]**

[a] Saarland University, Department of Systems Engineering Saarbruecken, 66123, Germany, tim.grupp@uni-saarland.de

[b] Center for Mechatronics and Automation Technology (ZeMA gGmbH), Saarbruecken, 66121, Germany

## ABSTRACT

As an emerging and innovative solid-state technology, elastocaloric cooling has been considered a promising alternative to conventional vapor compression refrigeration due to its high coefficient of performance and zero global warming potential. However, the commercialization of tension-based systems is critically limited by the fatigue life of the employed Shape Memory Alloys (SMAs) undergoing cyclic mechanical loading. To address this challenge, this contribution investigates the fatigue behavior, material lifetime and failure mechanisms associated with NiTi SMAs, which are widely used for elastocaloric applications. A predictive computational framework is developed in COMSOL Multiphysics by combining a generalized phase-field model for fracture with a fatigue degradation function and the constitutive Mueller-Achenbach-Seelecke SMA model, based on statistical thermodynamics. Fatigue crack nucleation, propagation, and subcritical crack growth are predicted, providing insights into the underlying failure mechanisms. These findings enable early detection of fatigue damage, contributing to enhanced reliability and performance of elastocaloric systems.

**Keywords:** Elastocaloric Effect, Shape Memory Alloys, Fatigue, Phase-Field Model, Finite Element Analysis

**References:**

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# TUNING TRANSFORMATION TEMPERATURES IN CU–AL–MN SHAPE-MEMORY ALLOYS THROUGH SN ADDITION FOR ELASTOCALORIC COOLING

**Lovro Cigić*[(a)], Jaka Tušek[(b)], Aleš Nagode[(a)], Andrej Žerovnik[(b)], Blaž Karpe[(a)]**

[(a)] University of Ljubljana, Faculty of Natural Sciences and Engineering (UL NTF), Aškerčeva cesta 12, 1000 Ljubljana, Slovenia

[(b)] University of Ljubljana, Faculty of Mechanical Engineering (UL FS), Aškerčeva cesta 6, 1000 Ljubljana, Slovenia

*Corresponding author: Lovro Cigić, +3861 2000 415, lovro.cigic@ntf.uni-lj.si

## ABSTRACT

Efficient elastocaloric cooling requires low-hysteresis shape-memory alloys that are fully austenitic at the operating temperature. Cu–Al–Mn-based shape-memory alloys are promising candidates; however, precise control of their transformation temperatures remains challenging. This study examines the effect of Sn addition on the transformation behaviour of as-cast CuAl9Mn9.5 alloys. Alloys containing 0.75, 1.5, and 2.5 wt.% Sn were prepared by arc melting, cast into a copper mould, and characterised using EDXS, differential scanning calorimetry (DSC), resistance–temperature measurements, and elastocaloric testing. EDXS confirmed good chemical uniformity, while Sn addition systematically lowered all transformation temperatures (Ms, Mf, As, and Af). In particular, Af decreased from 102.4 °C in the base CuAl9Mn9.5 alloy to −61.1 °C in CuAl9Mn9.5Sn2.5. This shift was accompanied by a room-temperature microstructural transition from martensitic plate/lath morphology to predominantly austenitic equiaxed grains. These findings demonstrate that even small Sn additions strongly tune Cu–Al– Mn alloys for room-temperature elastocaloric behaviour, supporting their potential for cooling applications.

**Keywords**: Cu–Al–Mn Shape-memory Alloys, Sn Addition, Transformation Temperatures, Microstructure, Elastocaloric Cooling

# ADVANCING BAROCALORIC REFRIGERATION THROUGH ENHANCED THERMAL AND MECHANICAL PERFORMANCE OF SPIN CROSSOVER MATERIALS

**Aya Benjira*[(a)], Elen Duverger-Nédellec[(b)], Benjamin Bertin[(b)], Dominique Denux[(b)], Tatiana Chartier[(a)], Mathieu Marchivie[(b)], Philippe Guionneau[(b)], Patrick Rosa[(b)], Fabien Giovannelli[(a)], Guillaume Nataf[(a)]**

[(a)] GREMAN UMR 7347, IUT de Blois, 15 rue de la chocolaterie, CS 2903 41029 Blois Cedex, France

[(b)] ICMCB UMR5026, CNRS-Université de Bordeaux-Bordeaux INP, 87 avenue du Dr. Schweitzer 33600 Pessac, France

*Corresponding author: aya.benjira@univ-tours.fr

## ABSTRACT

The European Pathfinder Programme's FROSTBIT project focuses on developing new techniques for creating innovative refrigeration technology based on solid state cooling. Our current study will examine how to optimize the physical properties of the spin crossover (SCO) molecular complex, which has a number of very large barocaloric effects. These characteristics indicate that SCO is an excellent candidate for solid state refrigeration applications. In order to make functioning regenerative cooling devices from this material, it will be important to optimize the thermal pathways within this material to ensure the most efficient heat transfer during the refrigeration cycles. The primary objective of this research is to optimize the thermal conductivity of the SCO matrix. The secondary objective is to improve the mechanical properties of the SCO material to produce high density objects with sufficient strength for use in solid state refrigeration applications. Ultimately, the goal of the entire project is to determine the best thermal conductivity and heat capacity of the SCO material to provide the basic operational characteristics necessary for the next generation of sustainable refrigeration.

**Keywords**: Spin Crossover Materials, Barocaloric Refrigeration, Thermal Conductivity, sustainable refrigeration

# Multicaloric and multipyro materials

PB-48 Investigation of multicaloric effects in ferroelectrics under uniaxial compressive stress

**Sara Lafuerza** · *INMA-CSIC, Univ. de Zaragoza*

# INVESTIGATION OF MULTICALORIC EFFECTS IN FERROELECTRICS UNDER UNIAXIAL COMPRESSIVE STRESS

**Sara Lafuerza[a,b], Isabel Jiménez-Omeñaca[a,b], Javier Blasco[a,b], Gloria Subías[a,b], Vera Cuartero[a,c], David Gracia[a,b], Marco Evangelisti[a,b]**

[a]Instituto de Nanociencia y Materiales de Aragón (INMA), CSIC-Universidad de Zaragoza, Zaragoza, 50009, Spain

[b]Departamento de Física de la Materia Condensada, Universidad de Zaragoza, Zaragoza, 50009, Spain

[c]Departamento de Ciencia y Tecnología de Materiales y Fluidos, Universidad de Zaragoza, Zaragoza, 50009, Spain

## ABSTRACT

Recently, multicaloric (MuC) materials –those in which caloric effects can be controlled by multiple external fields (either simultaneously or sequentially)–have emerged as a promising route to enhance the thermal response and improve the caloric performance beyond that of single-caloric materials for widespread solid-state cooling applications (Hou, Qian and Takeuchi, 2022). While most investigations on MuC effects have focused on applying mechanical stimuli to prototypical magnetocaloric materials, here we investigate the influence of uniaxial compressive stress (σ) on the electrocaloric effect (ECE) of bulk ferroelectrics, *i.e.*, σ-mediated ECE. We have developed a custom-built setup that integrates a loading cell with force sensor, high-voltage application, and temperature control. Besides indirect σ-mediated ECE measurements via temperature-dependent polarization experiments, this setup is being further upgraded to enable direct measurements using a high-speed infrared camera. The technical developments and preliminary σ-mediated ECE results on perovskite ferroelectric reference materials will be presented.

**Keywords:** ferroelectrics, electrocaloric, multicaloric, compressive stress

**References:** Hou, H., Qian, S. and Takeuchi, I. (2022) 'Materials, physics and systems for multicaloric cooling', *Nature Reviews Materials*, 7(8), pp. 633–652. doi: 10.1038/s41578-022-00428-x.

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# Thermoelectric & magneto-thermoelectric materials

PB-49 Flexible design and microfabrication of a Si-based µTEG platform for heterogeneous thermoelectric material integration
**Marc Aceituno** · *IMB-CNM-CSIC*

# FLEXIBLE DESIGN AND MICROFABRICATION OF A SI-BASED µTEG PLATFORM FOR HETEROGENEOUS THERMOELECTRIC MATERIAL INTEGRATION

**Marc Aceituno, Alex Rodríguez-Iglesias, Shahadev Rodríguez-Miguel, Iñigo Martín, Joaquín Santander, Luis Fonseca, Llibertat Abad, Marc Salleras**

Institute of Microelectronics of Barcelona (IMB-CNM, CSIC) Campus UAB, E-08193, Cerdanyola del Vallès (Barcelona), Spain, marc.aceituno@imb-cnm.csic.es

## ABSTRACT

The increasing demand for autonomous and decentralized power sources to supply IoT nodes is driving interest in environmental energy harvesting technologies, such as thermoelectric generators (TEGs), which convert waste-heat into electricity in a compact, solid-state form. While research has mainly focused on improving the material thermoelectric figure of merit (zT), µTEG performance also critically depends on device architecture and thermal management to maximize the temperature gradient across the thermoelectric material (Calaza et al., 2016; Ferrando-Villalba et al., 2019).

Building on our group's previous development of silicon-based µTEG platforms integrating nanostructured thin films (Perez-Marín et al., 2014), we present a MEMS-compatible, microfabricated planar µTEG platform for the integration and evaluation of novel thin-film thermoelectric materials within a fully operational device. The platform provides versatile material integration through multiple deposition routes, including direct deposition and etching, as well as shadow-mask methods that avoid subsequent patterning. In addition, the platform allows last-stage material deposition, eliminating the need for additional lithography steps.

**Keywords:** energy harvesting, micro-thermoelectric generator (µTEG), microfabrication, thin-film.

**References:**

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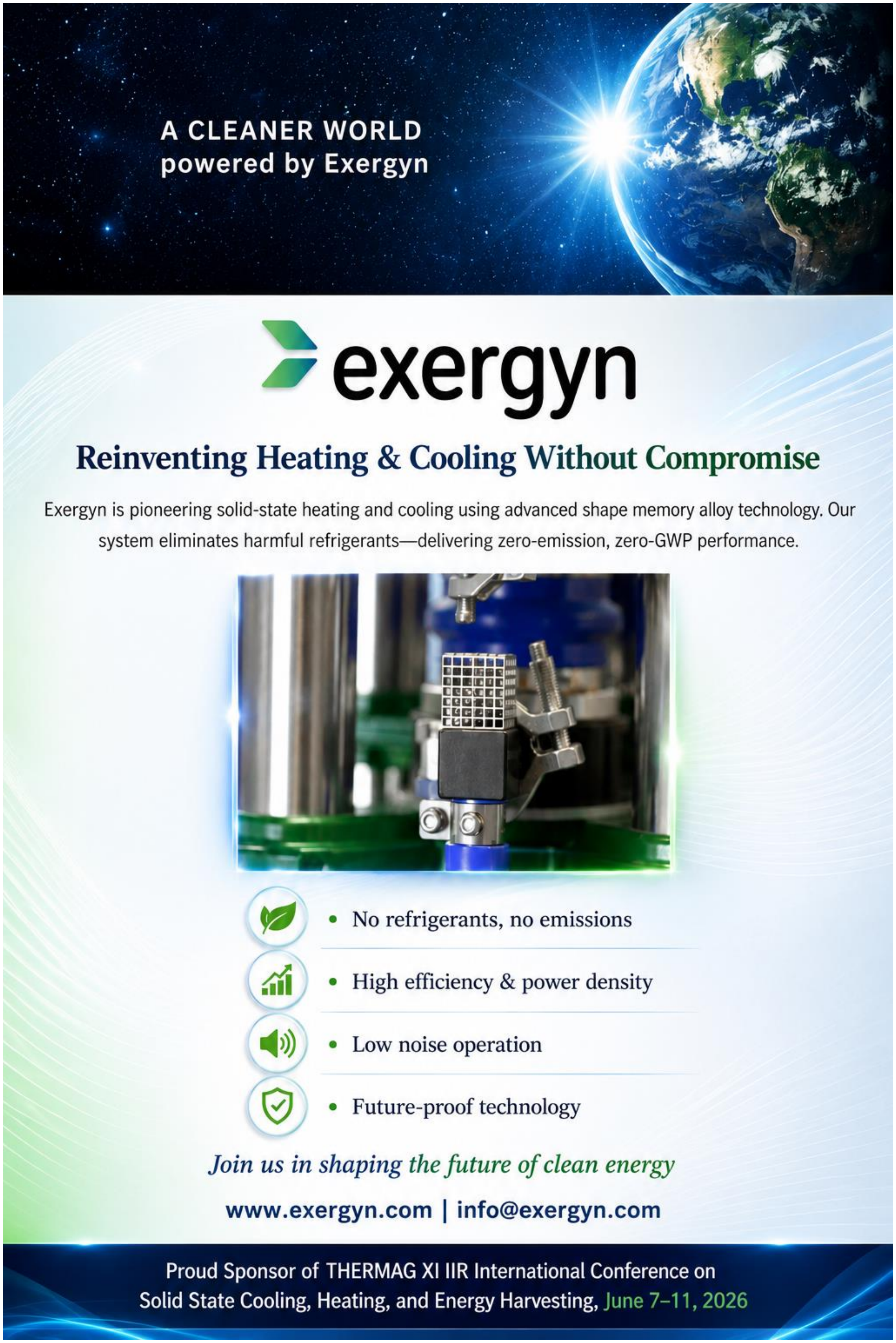
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