LAHDE
LABORATORY FOR REFRIGERATION AND DISTRICT ENERGY

University *of* Ljubljana
Faculty *of* Mechanical Engineering

MAGNETIC REFRIGERATION AT THE UNIVERSITY OF LJUBLJANA

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Jaka Tusek, Urban Tomc, Uros Plaznik, Marko Ozbolt, Alojz Poredos

UNIVERSITY OF LJUBLJANA
Faculty of Mechanical Engineering

Delft Days on Magnetocalorics 2013
October 28-29 2013
Aula Congress Centre TU Delft, Mekelweg 2, Delft
TU Delft Delft University of Technology

Alternative Refrigeration & Heat Pump technologies

Heat & Mass Transfer	Solid State Refrigeration
Regenerators	*Magnetocalorics*
Thermal diodes	*Electrocalorics*
Solid State Thermal diodes	*Alternative Solid State Refrigeration*
Microfluidic Thermal diodes	

No technology without efficient and fast heat transfer !

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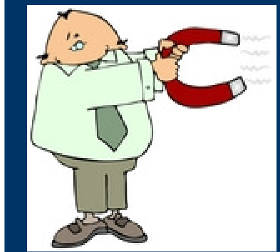
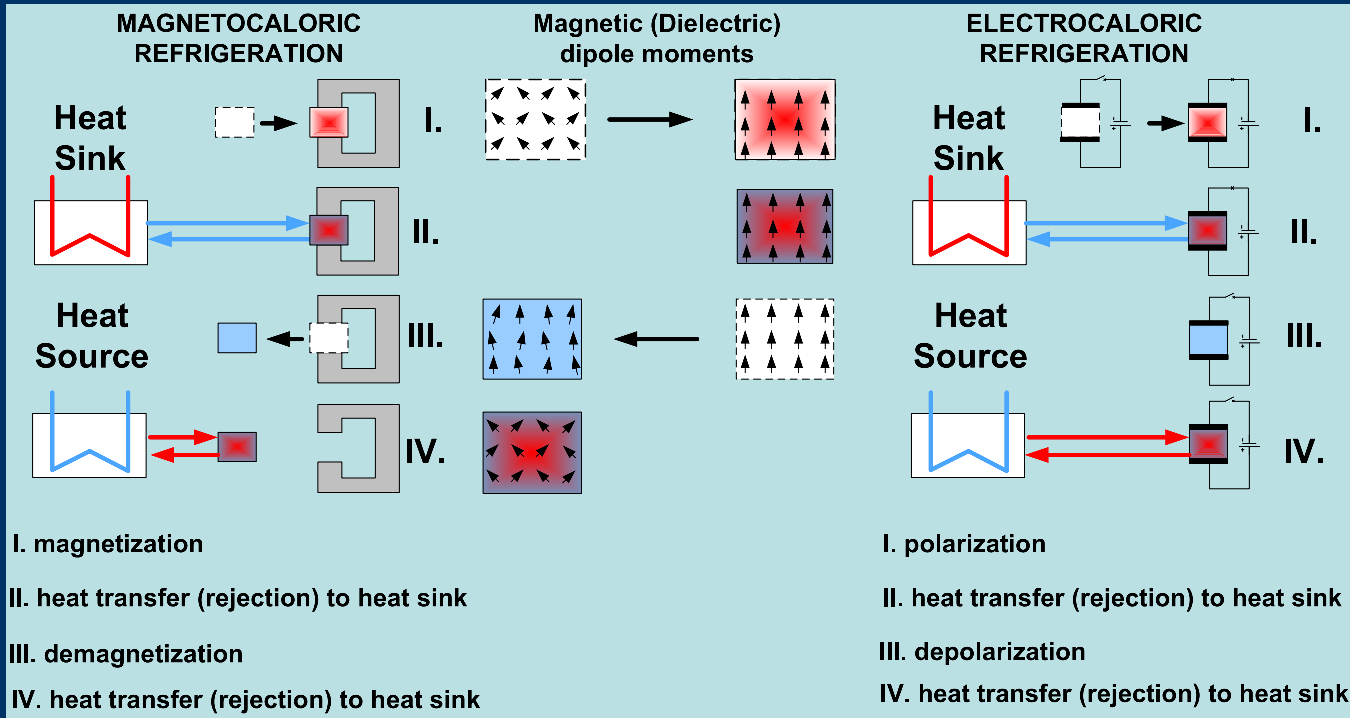
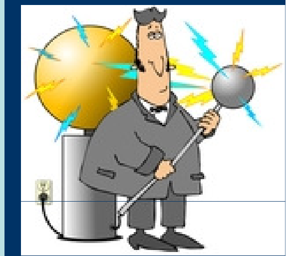
How does magnetocaloric or electrocaloric heat pump work?







1. Polarization ≡ Compression / Magnetization ≡ Compression
2. Heat transfer to heat sink≡ Condensation
3. Depolarization ≡ Expansion / Demagnetization ≡ Expansion
4. Heat transfer from heat source ≡ Evaporation

Magnetic Refrigeration at UL since 2004

WHAT WE DO

- Numerical simulations on regenerators, thermodynamic cycles, magnets (Matlab, Ansys)
- Experimental tests on regenerators, processing of regenerators, valve systems
- Conceptual designs & Prototyping

Numerics and theoretical work

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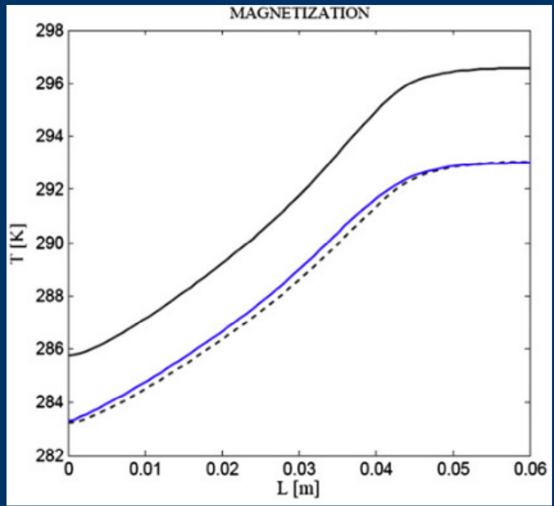
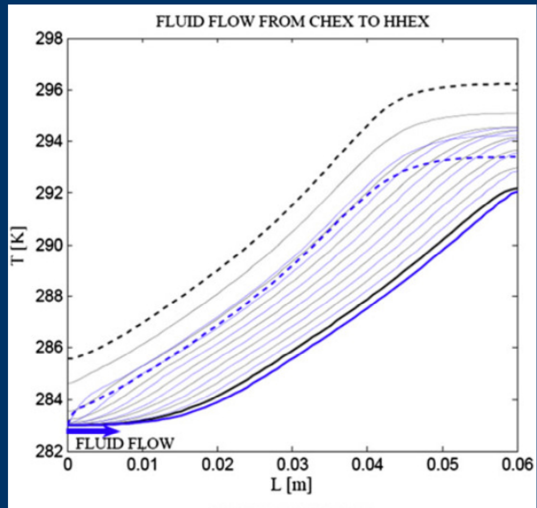
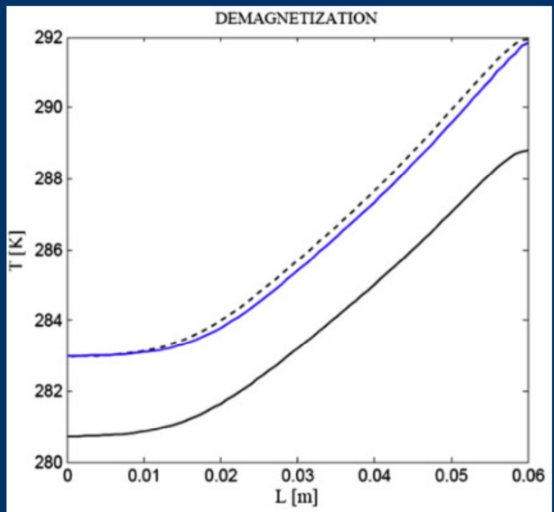
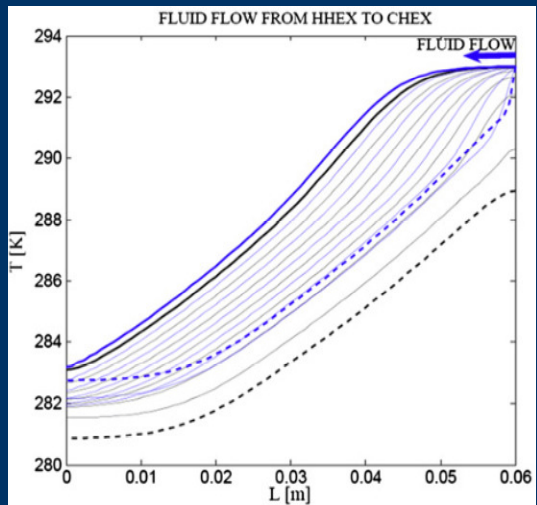
Matlab simulations on dynamic operation of AMRs









Tusek, J., Kitanovski, A., Prebil, I., Poredos, A., 2011. Dynamic operation of an active magnetic regenerator (AMR): numerical optimization of a packed-bed AMR. Int. J. Refrigeration 34 (6), 1507-1517.

Numerics and theoretical work

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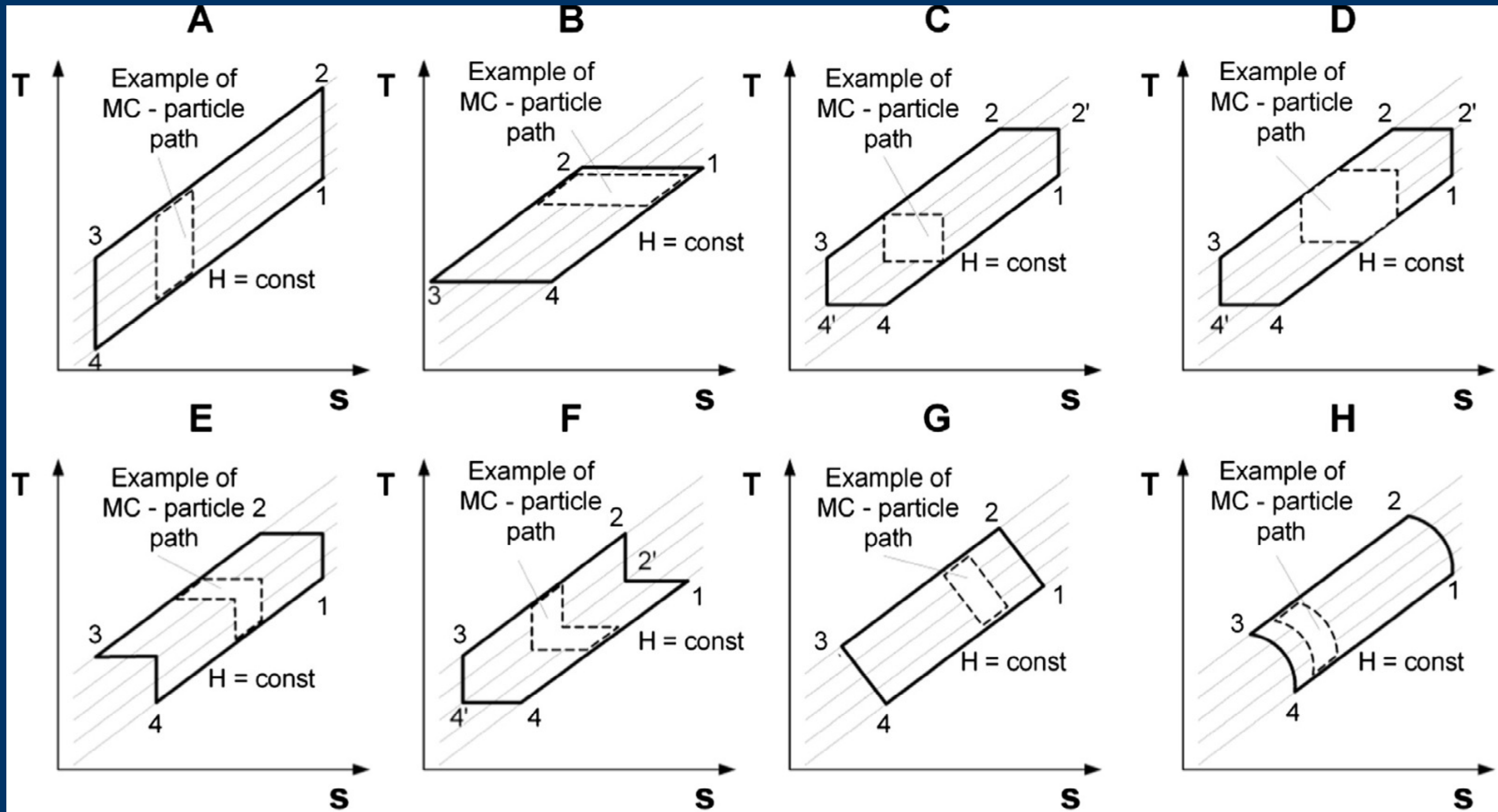
AMR thermodynamic cycles



Examples of magnetic refrigeration cycles with an AMR: A) Brayton with an AMR, B) Ericsson with an AMR, C) Carnot with an AMR, D) Hybrid BraytoneEricsson with an AMR, E-H) other potential new thermodynamic cycles.

Kitanovski, A., et al., New thermodynamic cycles for magnetic refrigeration, International Journal of Refrigeration (2013),

Numerics and theoretical work

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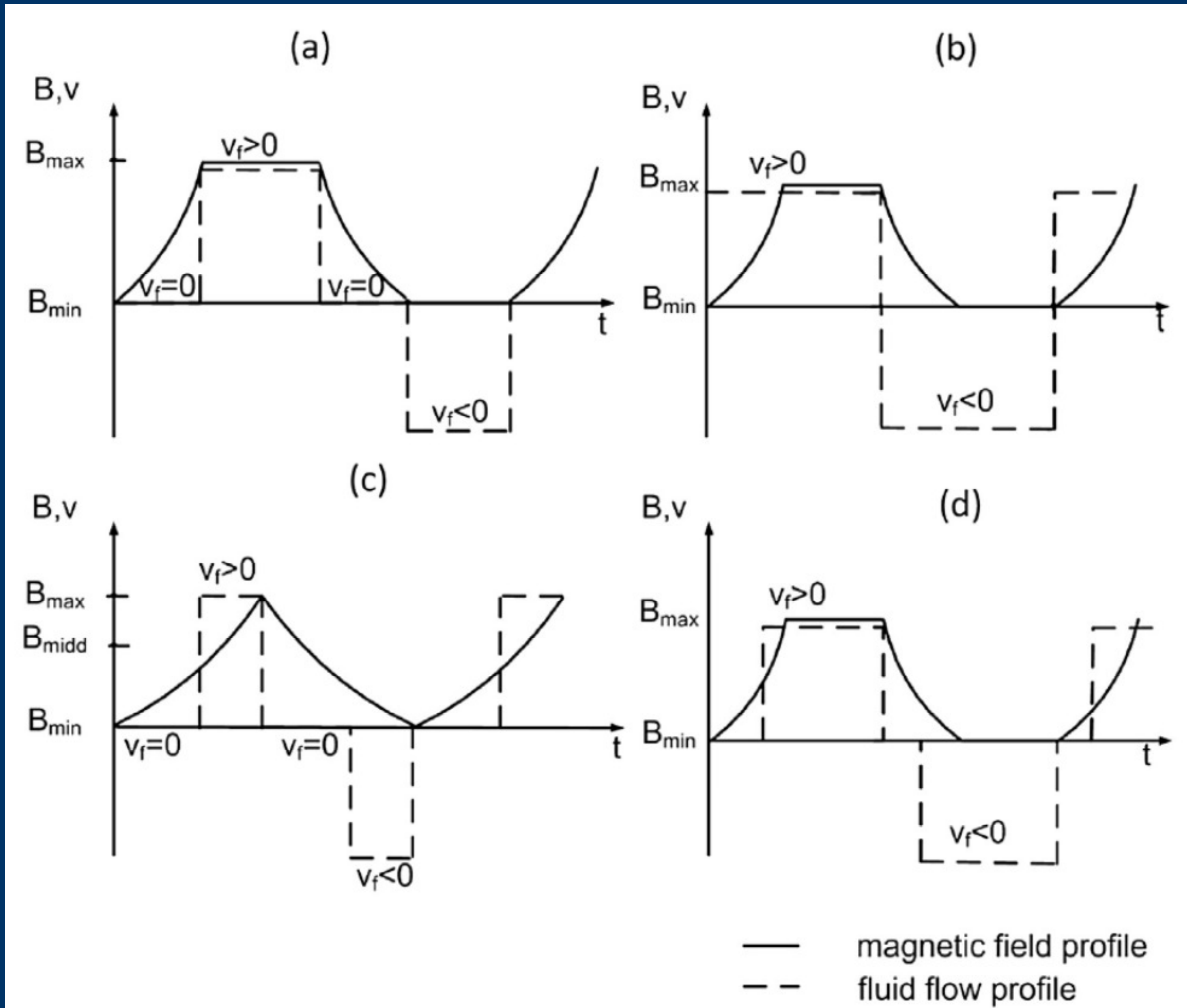
Matlab simulations on AMR thermodynamic cycles



Working regimes for different magnetic thermodynamic cycles with an AMR: (a) Brayton, (b) Ericsson, (c) Carnot, (d) Hybrid.

U. Plaznik et al. / Applied Thermal Engineering 59 (2013) 52-59

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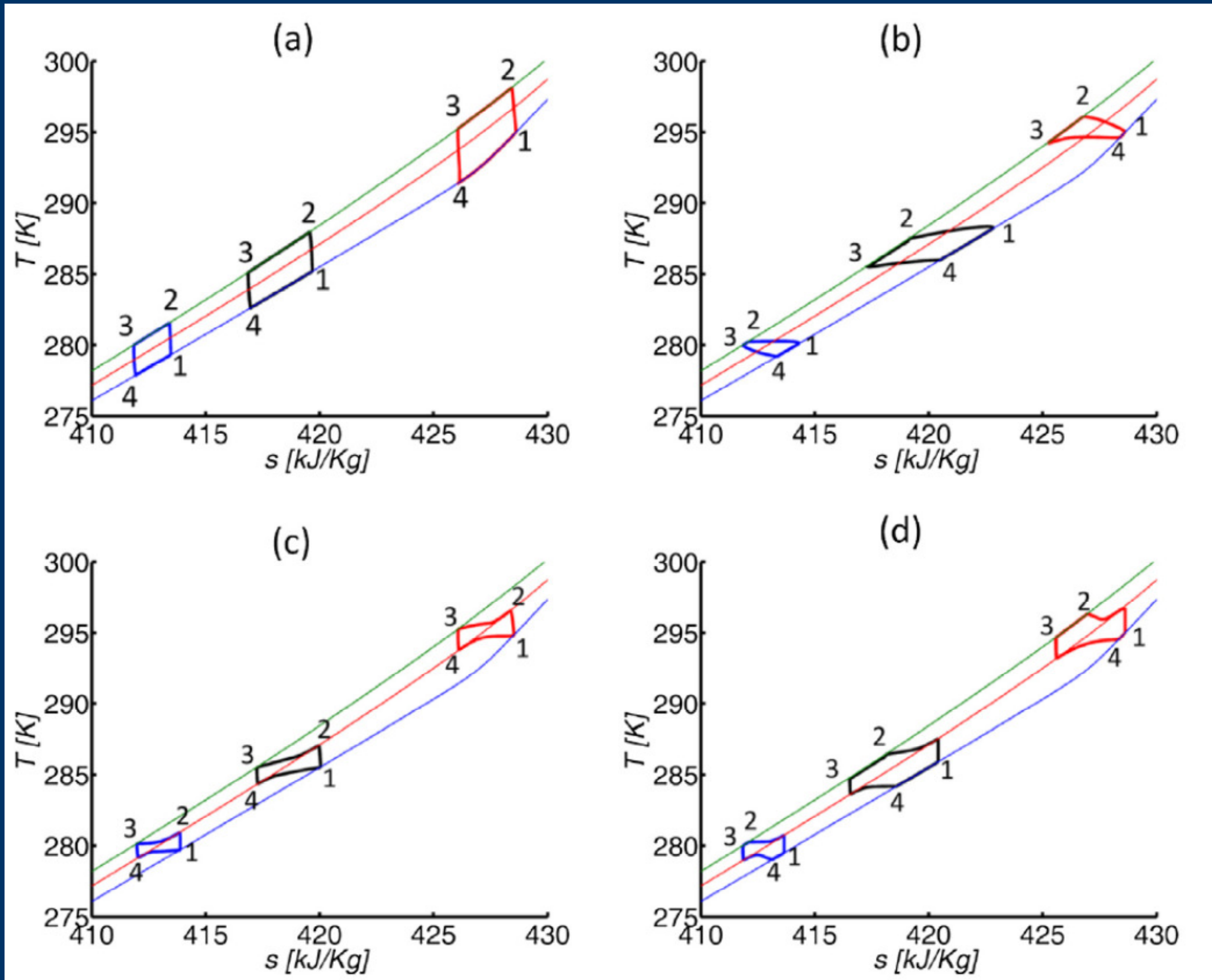
Numerics and theoretical work

Matlab simulations on AMR thermodynamic cycles

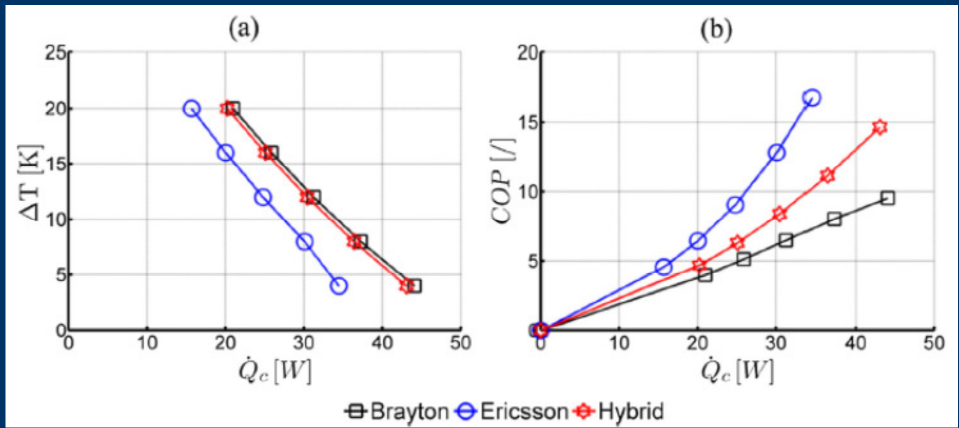


Magnetic refrigeration cycles with an AMR: (a) Brayton, (b) Ericsson, (c) Carnot, (d) Hybrid Braytone-Ericsson.

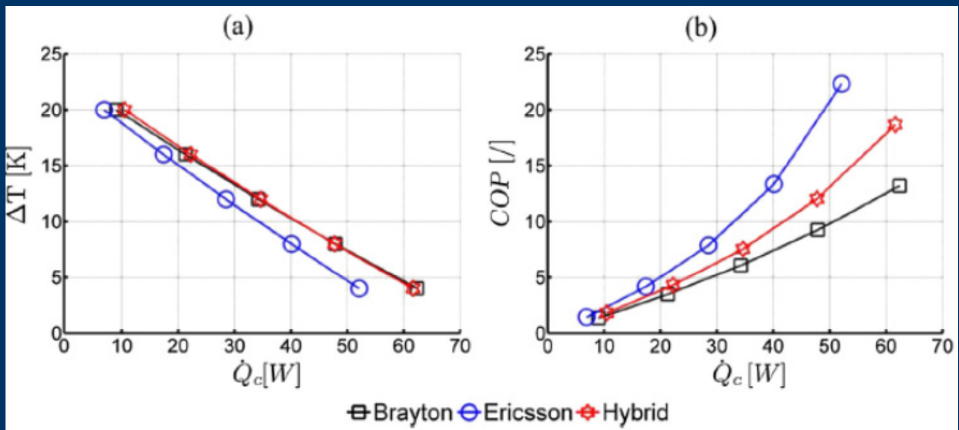
U. Plaznik et al. / Applied Thermal Engineering 59 (2013) 52-59

Numerics and theoretical work

Matlab simulations on AMR thermodynamic cycles



Results of numerical simulations for packed-bed AMR. (a) Influence of cooling power on the temperature span. (b) Influence of cooling power on the COP.



Results of numerical simulations for parallel-plate AMR. (a) Influence of cooling power on the temperature span. (b) Influence of cooling power on the COP.

U. Plaznik et al. / Applied Thermal Engineering 59 (2013) 52-59

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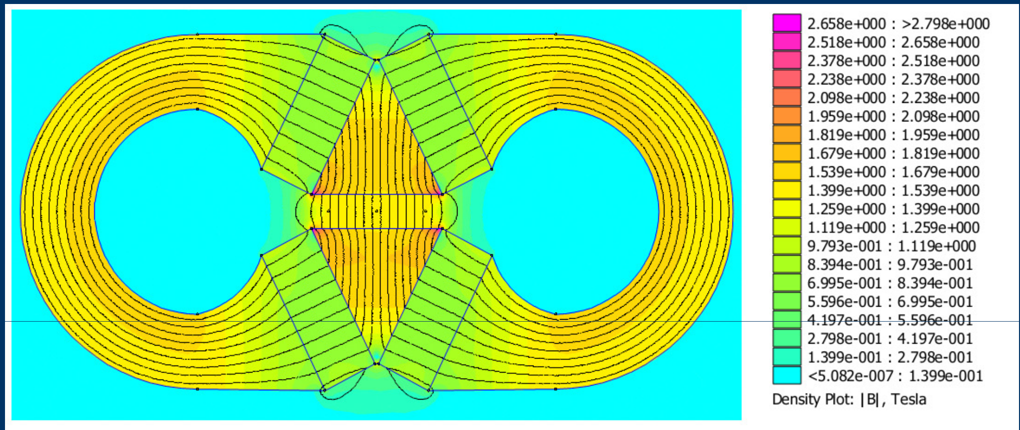
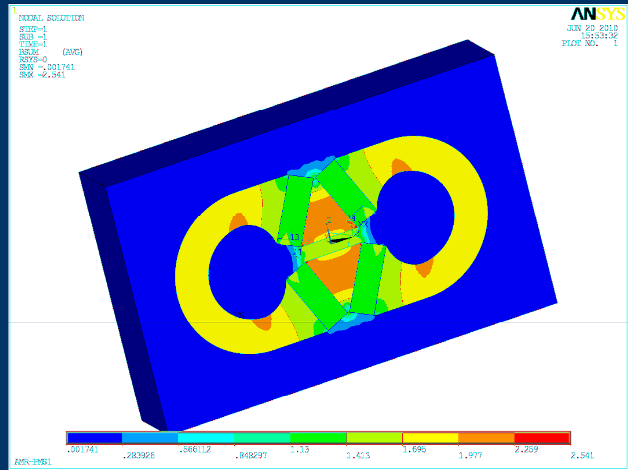
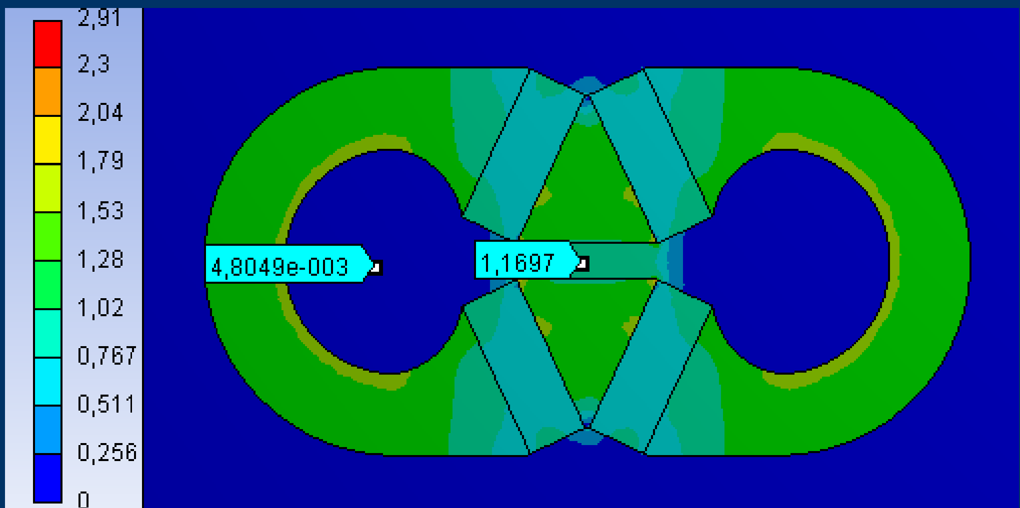
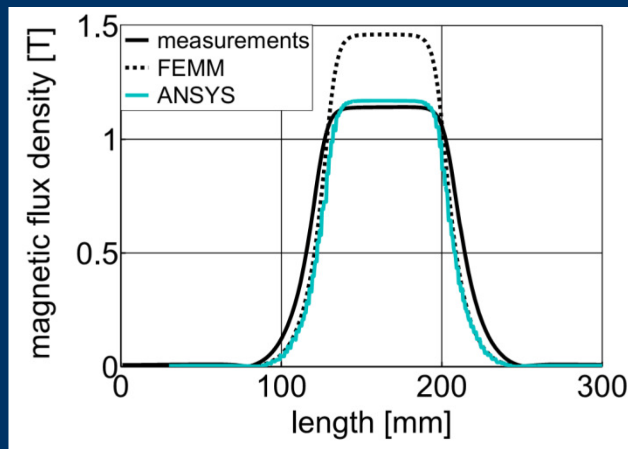
Numerics and theoretical work

Magnets (first designs by FEMM, later optimization with ANSYS Multiphysics)





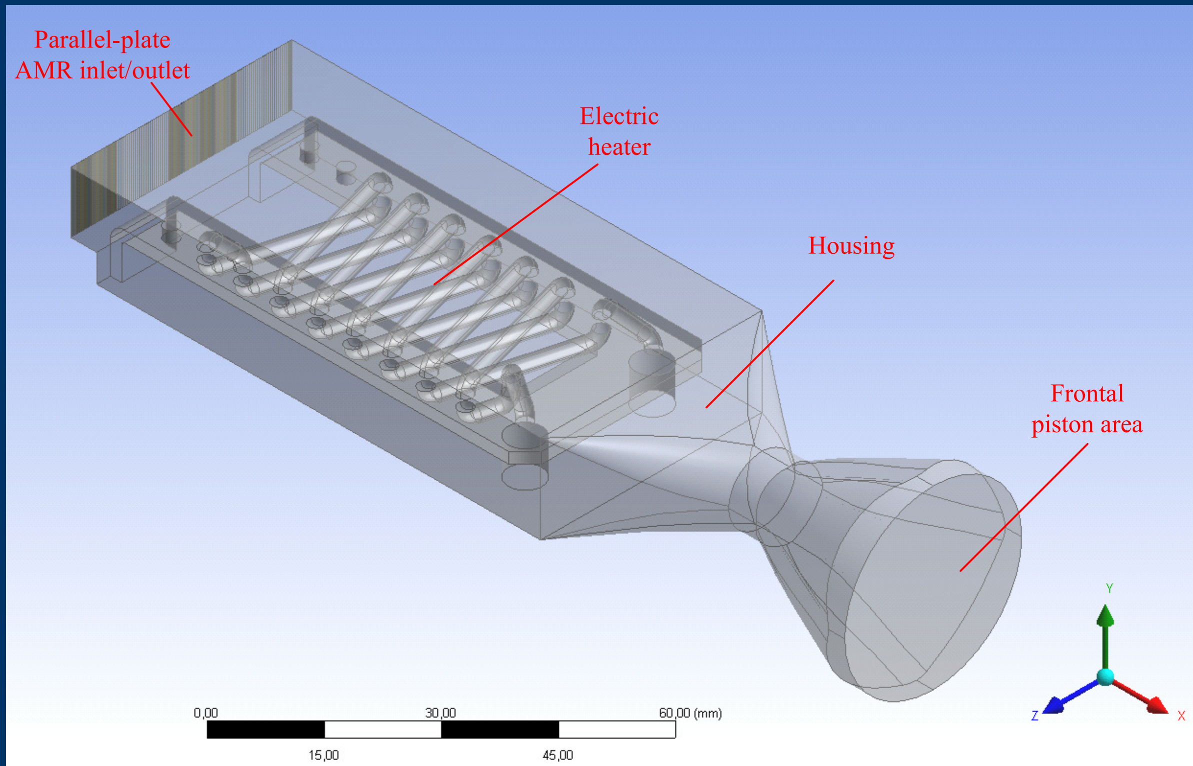




Tušek et al, The 5th International Conference on Magnetic Refrigeration at Room Temperature, Grenoble, France. 2012

Numerics and theoretical work

Ansys – Fluent simulations on coupled fluid dynamics, heat transfer



The geometry of the cold side heat exchanger of the AMR experimental device

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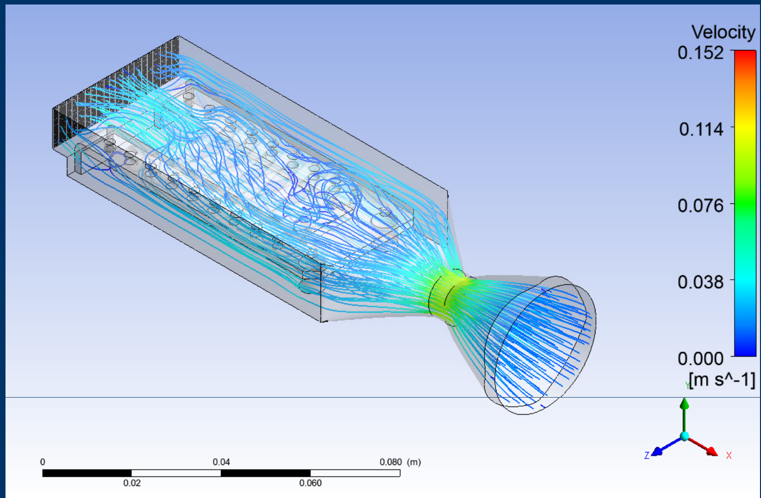
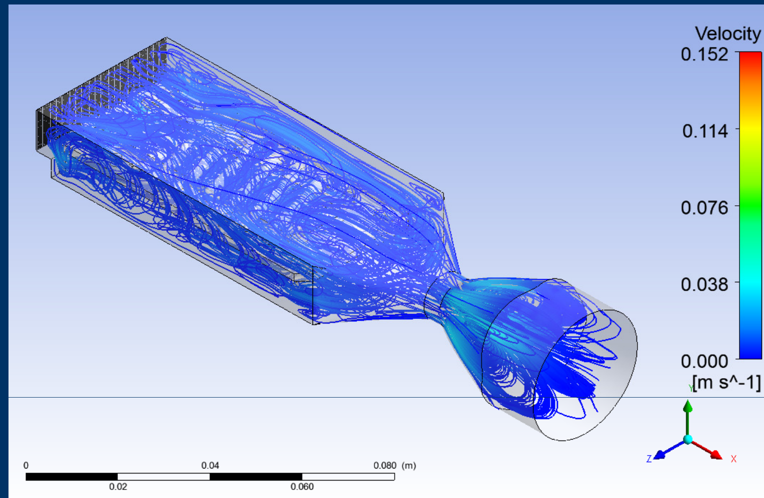
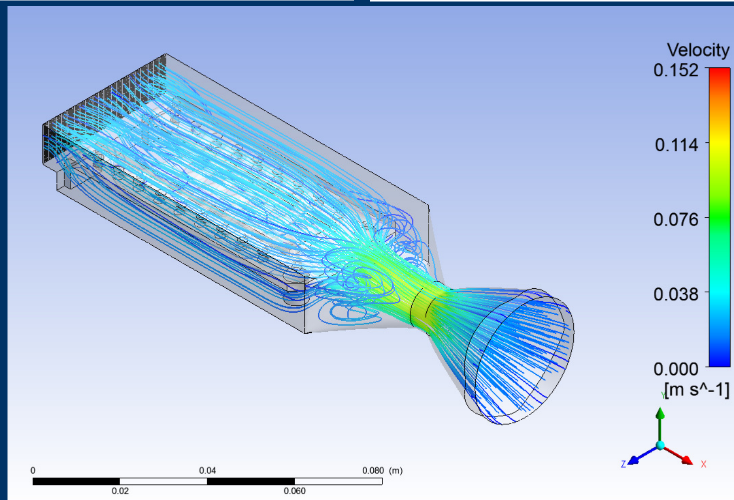
Numerics and theoretical work

Ansys – Fluent simulations on coupled fluid dynamics, heat transfer







Stream lines of the working fluid (above-piston moving in x-direction, mid-piston stopped, below-piston moving in the opposite direction)

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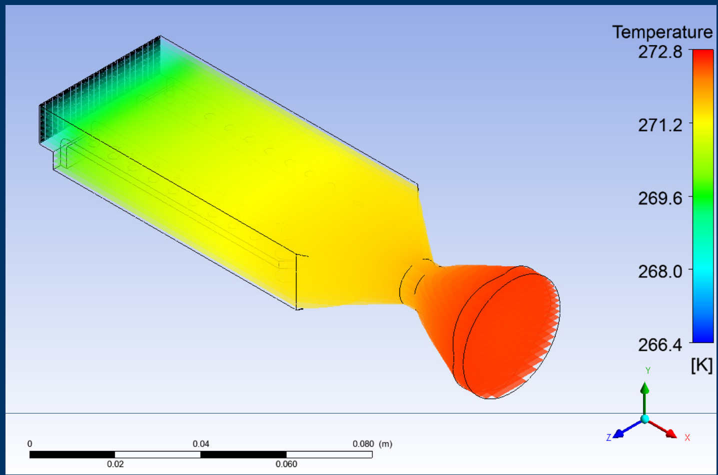
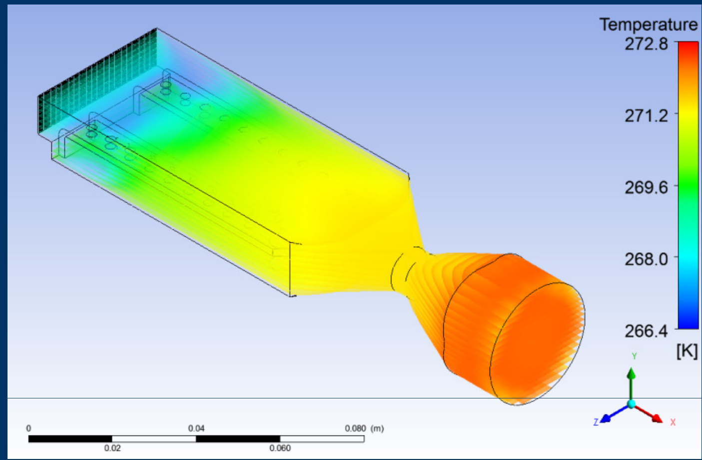
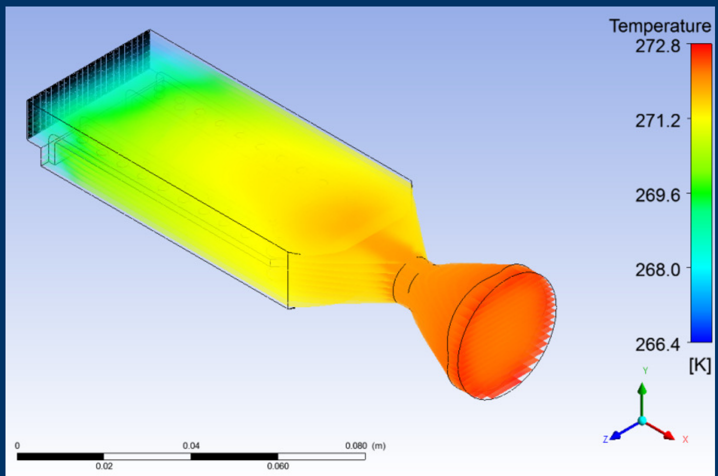
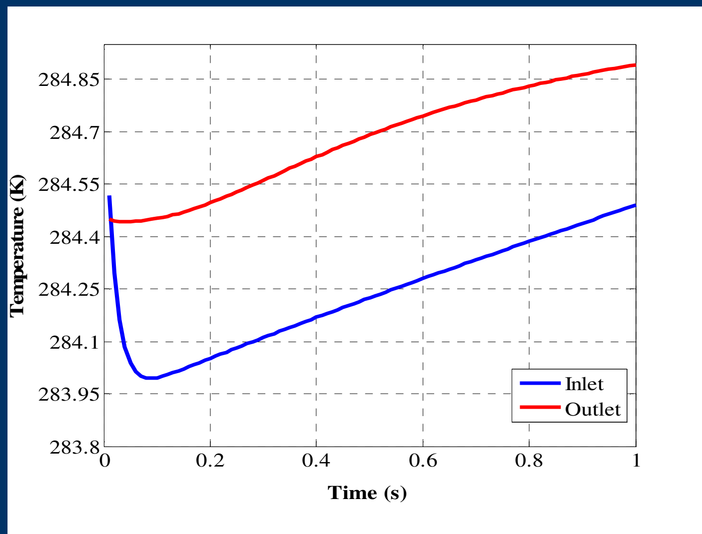
Numerics and theoretical work

Ansys – Fluent simulations on coupled fluid dynamics, heat transfer









Inlet and outlet temperature profiles in the cold heat exchanger

Temperature profiles at the beginning of piston movement in x-direction (above), when piston stopped (mid) and at the end of piston moving in the opposite direction (below)

U.Tomc, Work on the PhD Thesis, 2013

Numerics and theoretical work

A note on thermal diodes

Thermal diode is a physical phenomenon, mechanism or a device in which it is possible to manipulate and control:

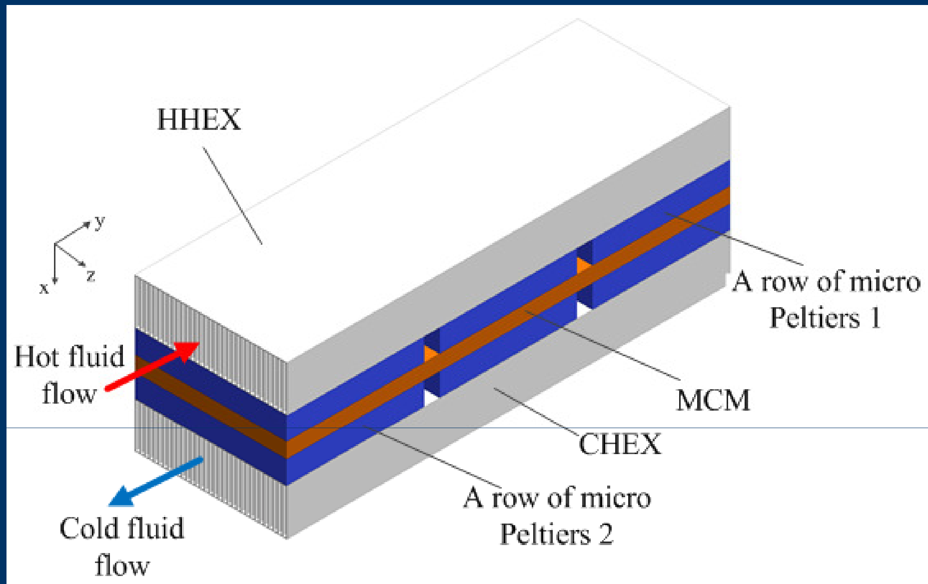
- Heat flux direction
- Heat flux rate

Possible domains for different kinds of applications as thermal diodes:

- Thermoelectrics
- Thermionics
- Spin-caloritronics
- Thermal rectification
- Electro-hydrodynamics
- Magneto-hydrodynamics

Numerics and theoretical work

Matlab simulations on thermal diodes



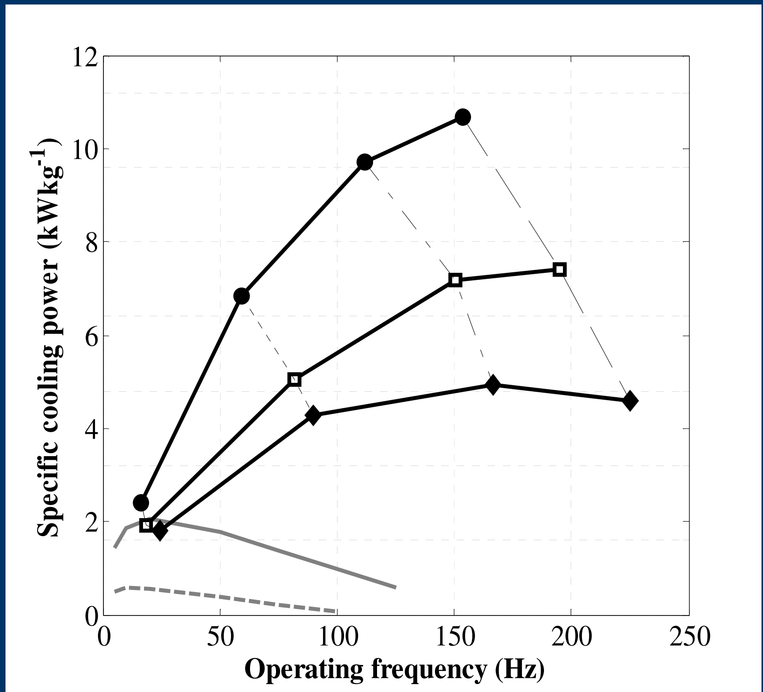
	MC device with thermal diodes
Magnetic field change	0–1T
MCM	gadolinium
Mass of the MCM	0.32 g
Dimensions	3.2×128×2.3 mm (x-y-z)
Geometry	one thin plate + thermal diodes
MCM plate thickness	0.1 mm
Working fluid	Water
Hot heat exchanger temperature	20℃

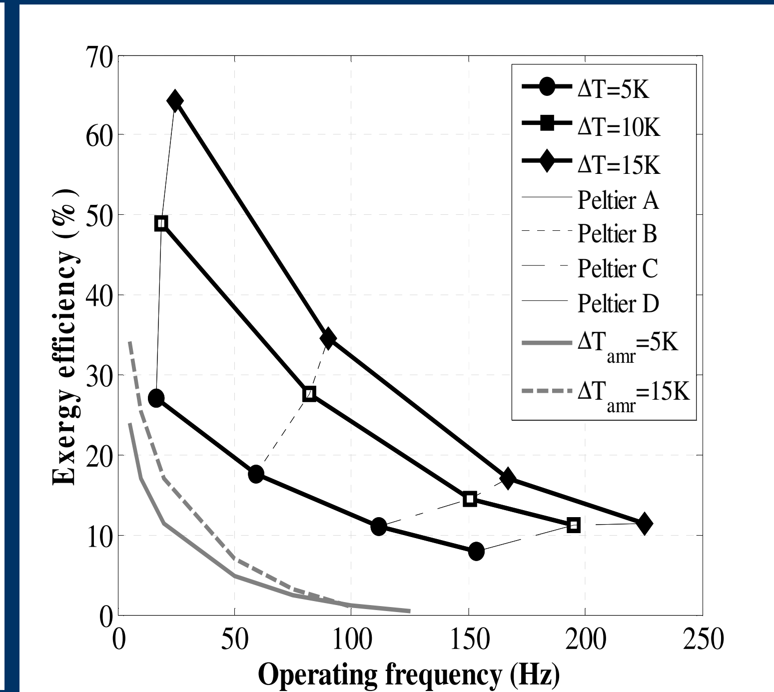
Thermal diode	Micro Peltier module	
	(W)	P_{Pe} (W)
Peltier A	0.041	0.0008
Peltier B	0.143	0.004
Peltier C	0.252	0.0103
Peltier D	0.327	0.0165
Dimensions	3.2×3.2×1 mm (x-y-z)	

Tomc, U., et al., A numerical comparison of a parallel-plate AMR and amagnetocaloric device with embodied micro thermoelectric thermal diodes, International Journal of Refrigeration (2013)

Numerics and theoretical work

Matlab simulations on thermal diodes





Comparison of the specific cooling powers and the exergy efficiencies of the parallel-plate AMR and the MC device with the thermal diodes at different operating frequencies and temperature spans.

Thermal diode	Micro Peltier module	
	(W)	P_{Pe} (W)
Peltier A	0.041	0.0008
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Tomc, U., et al., A numerical comparison of a parallel-plate AMR and amagnetocaloric device with embodied micro thermoelectric thermal diodes, International Journal of Refrigeration (2013)

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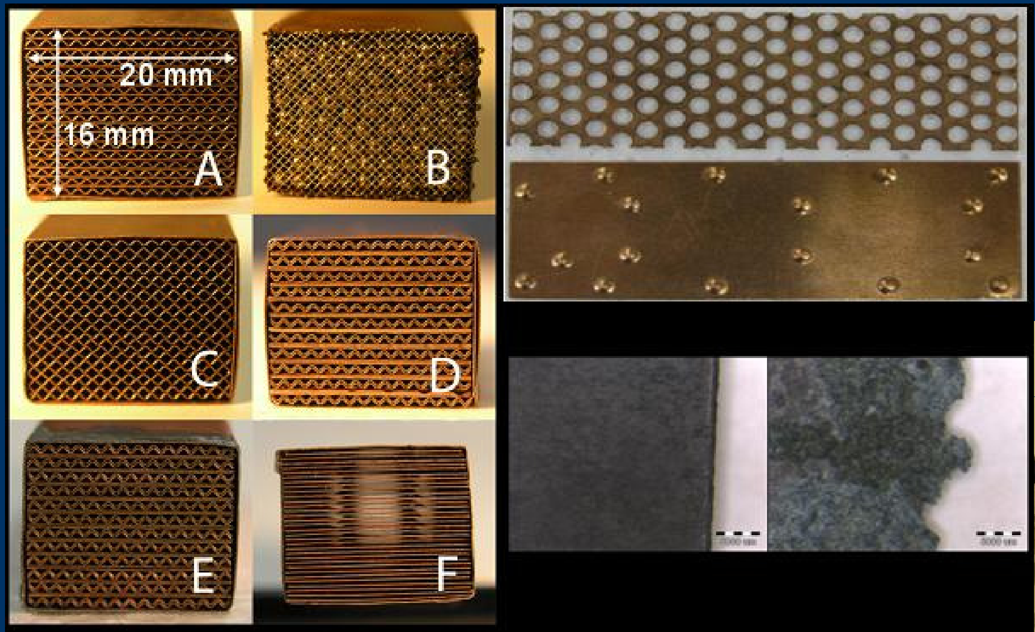
Experimental work

Early (2005) experimental tests on regenerators



Sarlah et al, International Journal of Refrigeration 29 (2006) 1332-1339
Sarlah et al, Journal of Mechanical Engineering 58(2012)1, SI 5

Design, simulation and experiments with the microchannel heat exchangers and regenerators. Corrosion tests with different materials and inhibitors.

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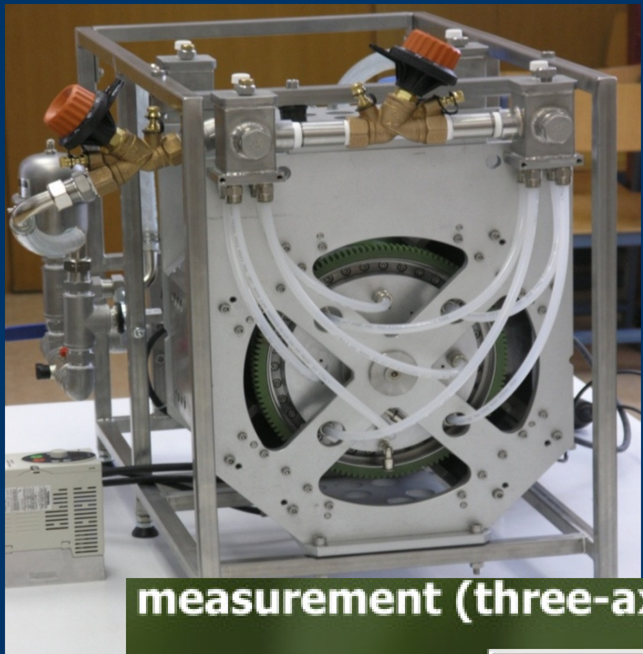
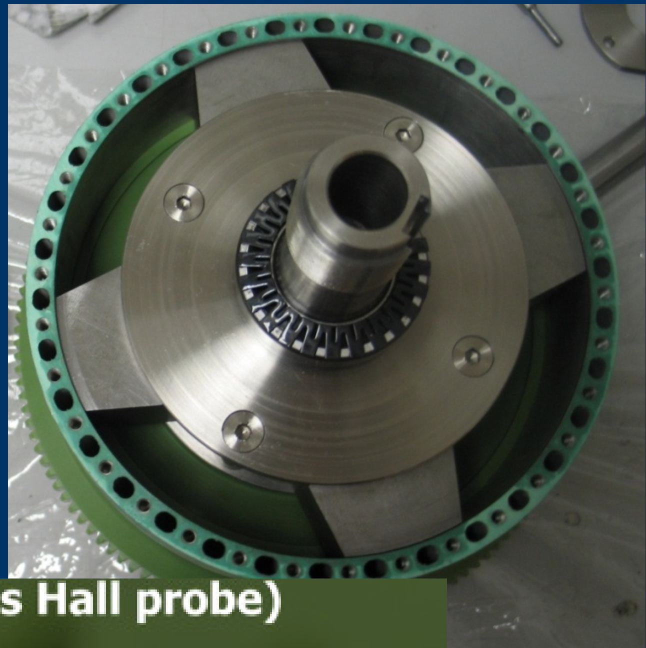
Experimental work

First prototype of a magnetic refrigerator (2005-2007)





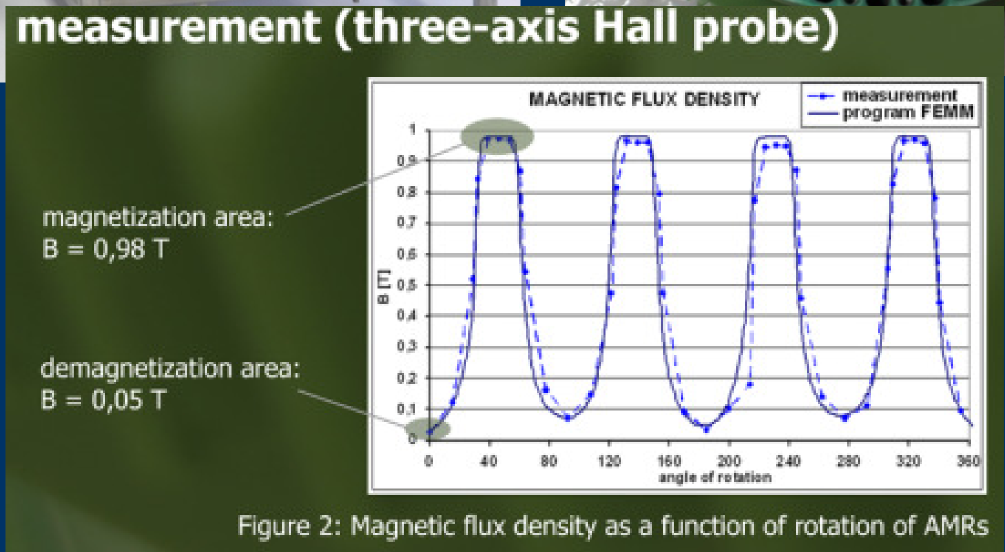


Figure 2: Magnetic flux density as a function of rotation of AMRs

Tušek et al, International journal of refrigeration 33 (2010) 294 – 300

Experimental work

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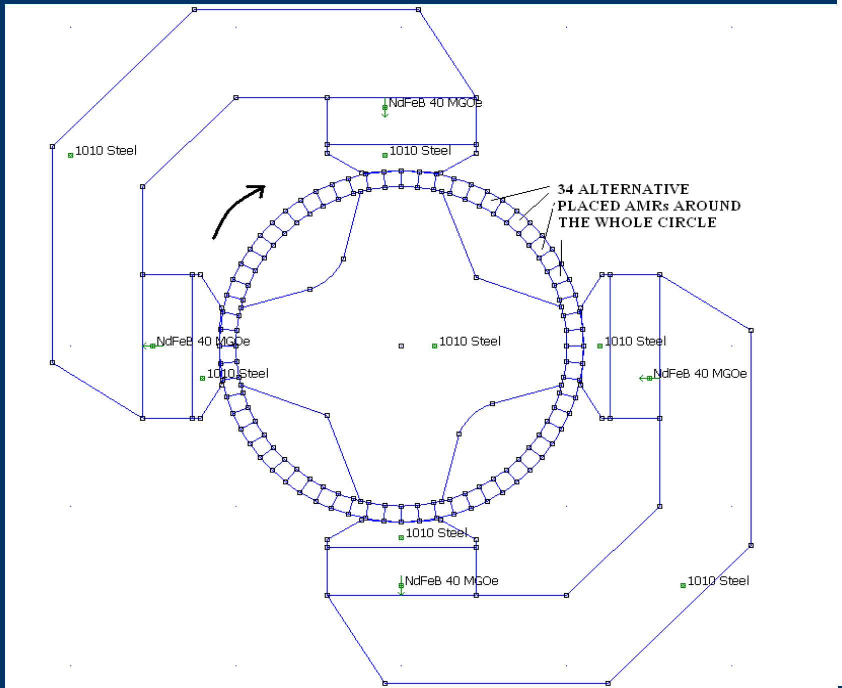
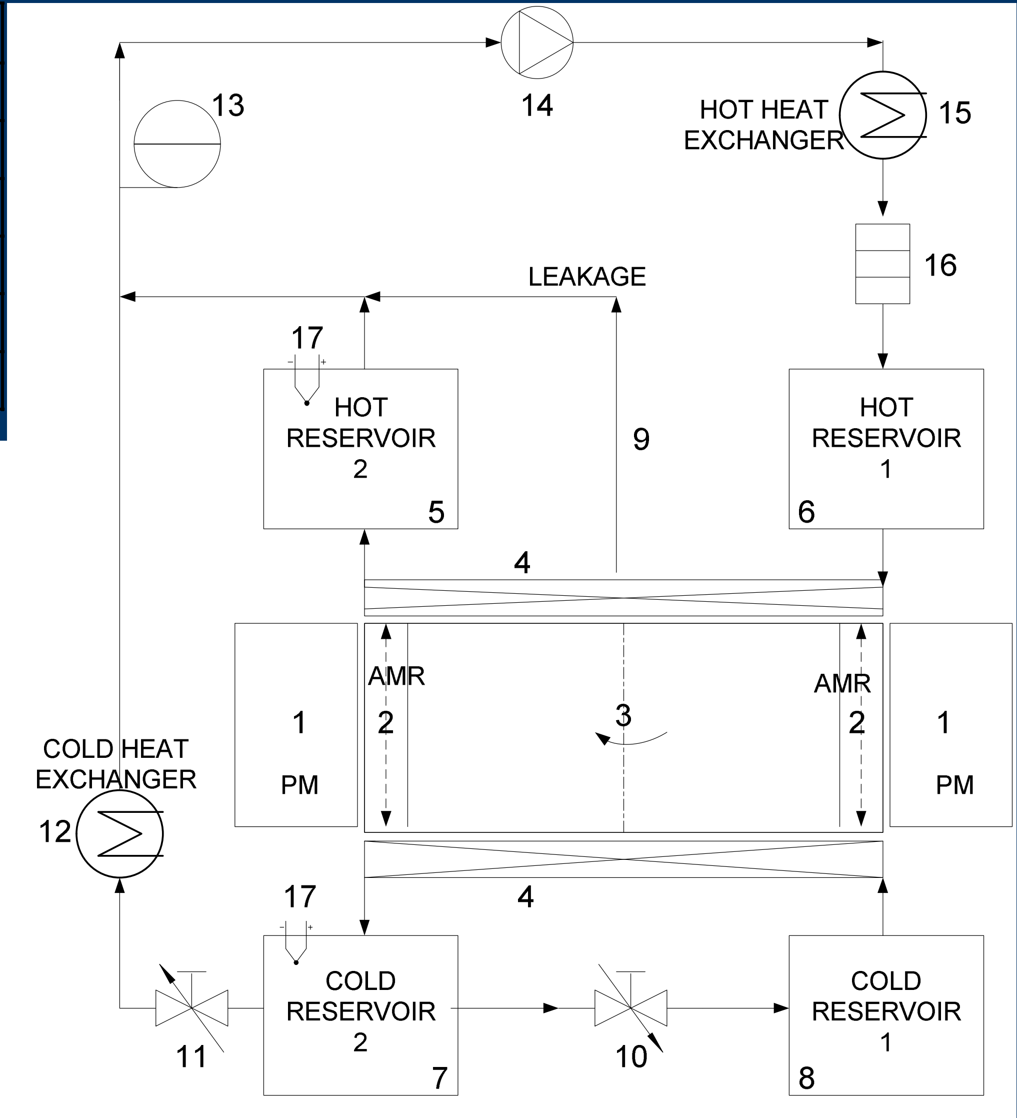
First prototype of a magnetic refrigerator (2005-2007)

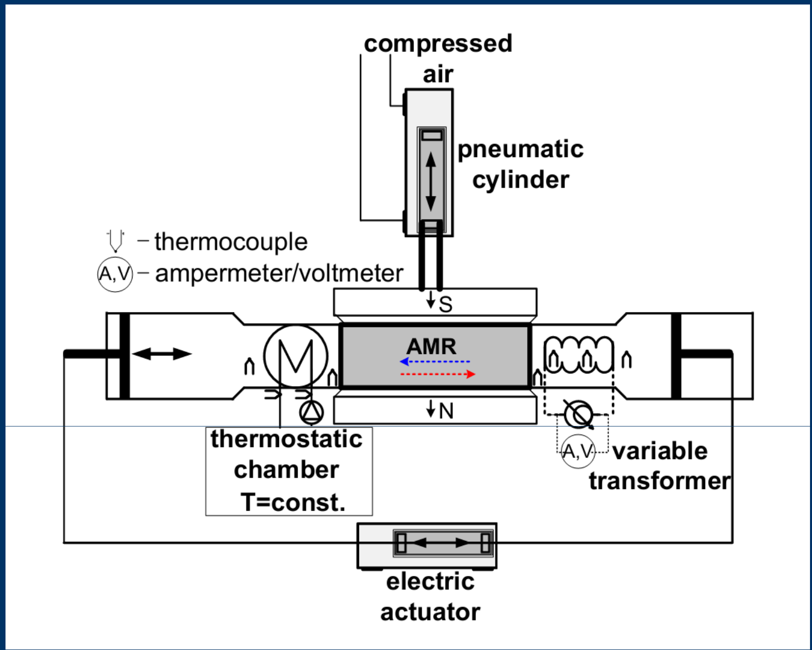
Magnetic field density	0.08 T – 0.97 T
Operating frequency	0 Hz – 4 Hz
Heat transfer fluid	Distilled water
Number of regenerator beds	34
Magnetocaloric material	Gd
Mass of magnetocaloric material	0.6 kg
Dimensions of regenerator bed	10mm x 10mm x 50 mm

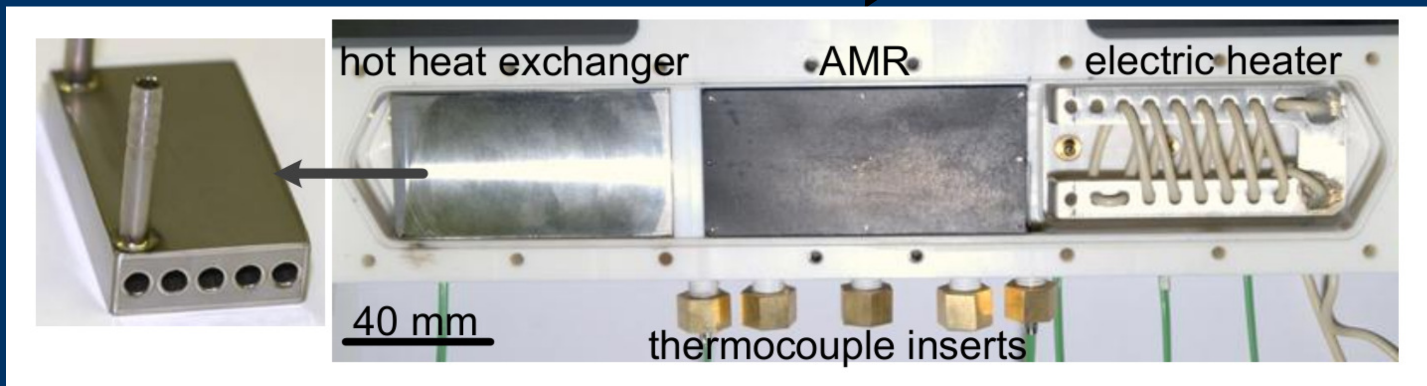




Experimental work

Experimental prototype (2012 -): Experimental tests on regenerators





Tusek et al, Applied Thermal Engineering 53 (2013) 57-66

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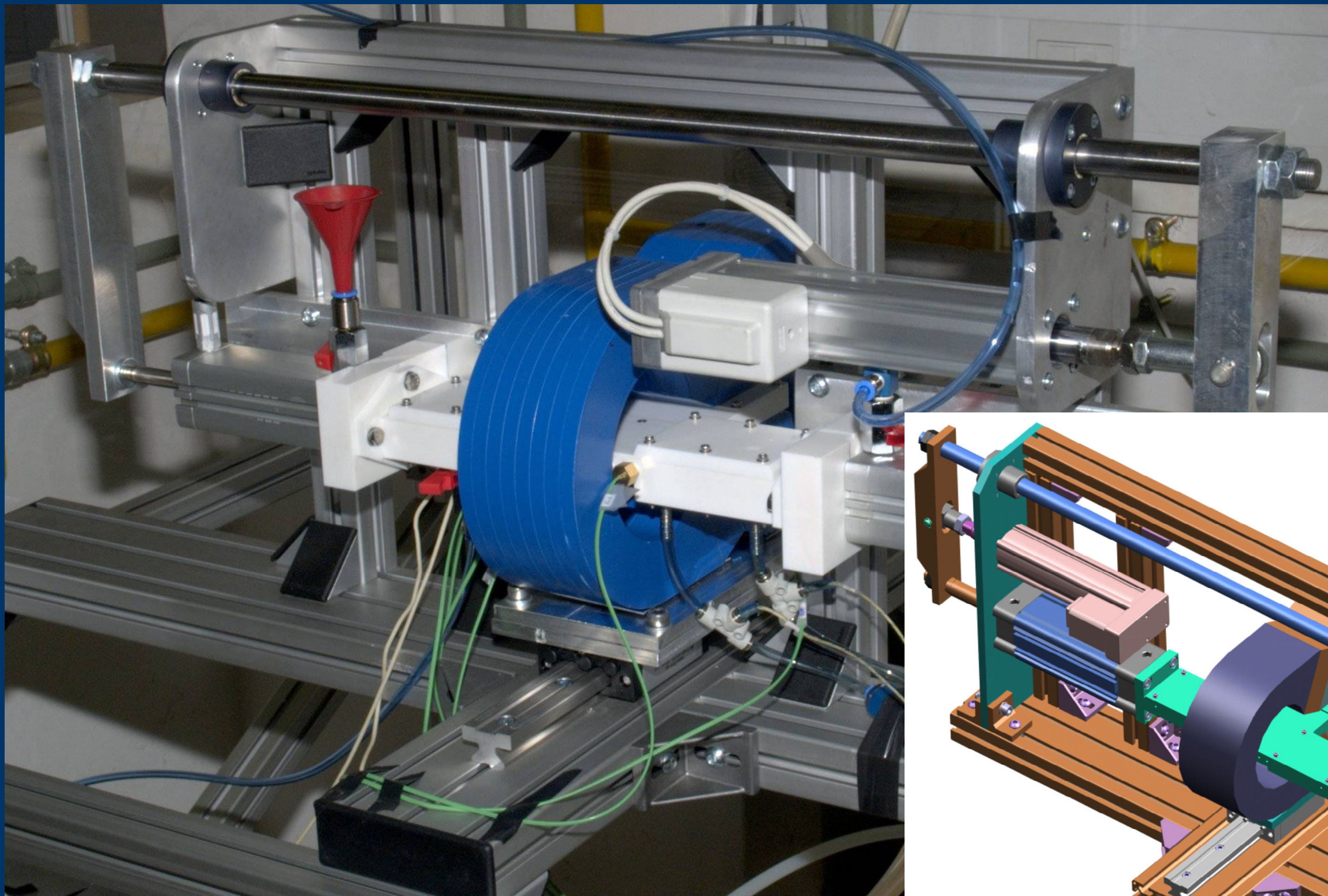
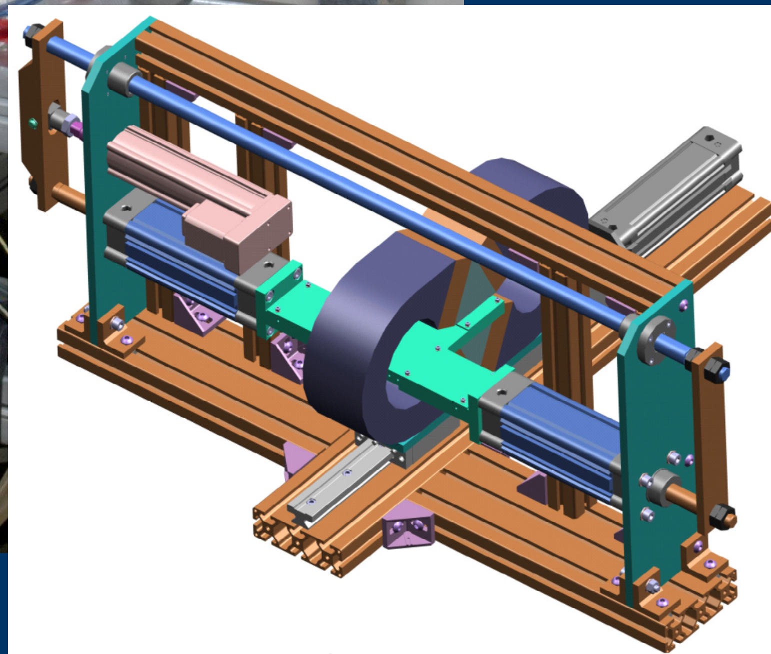
Experimental work

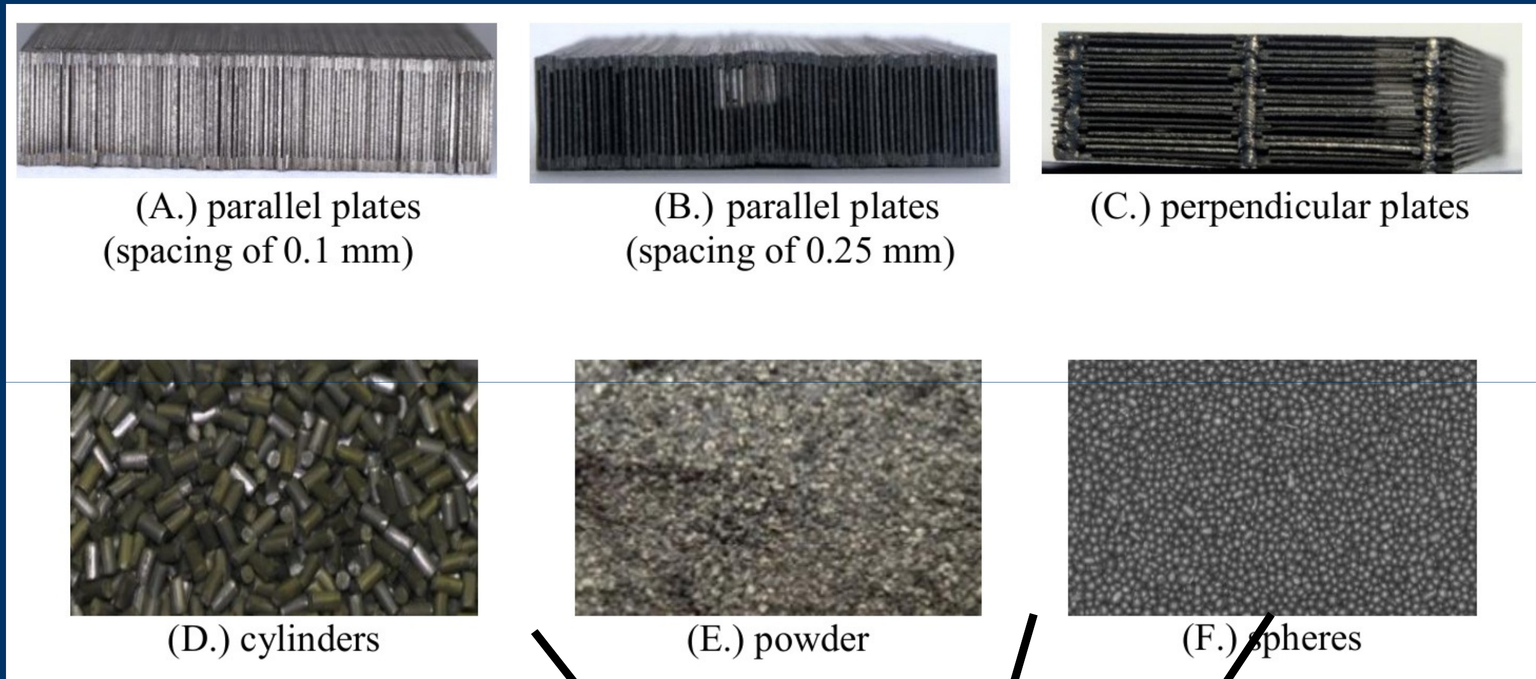


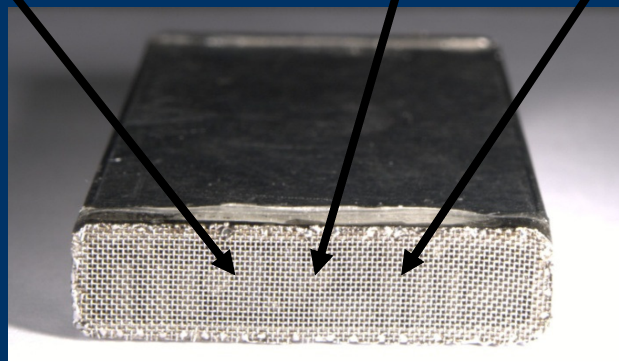


SMM

Experimental work

Magnetocaloric regenerators - Gadolinium

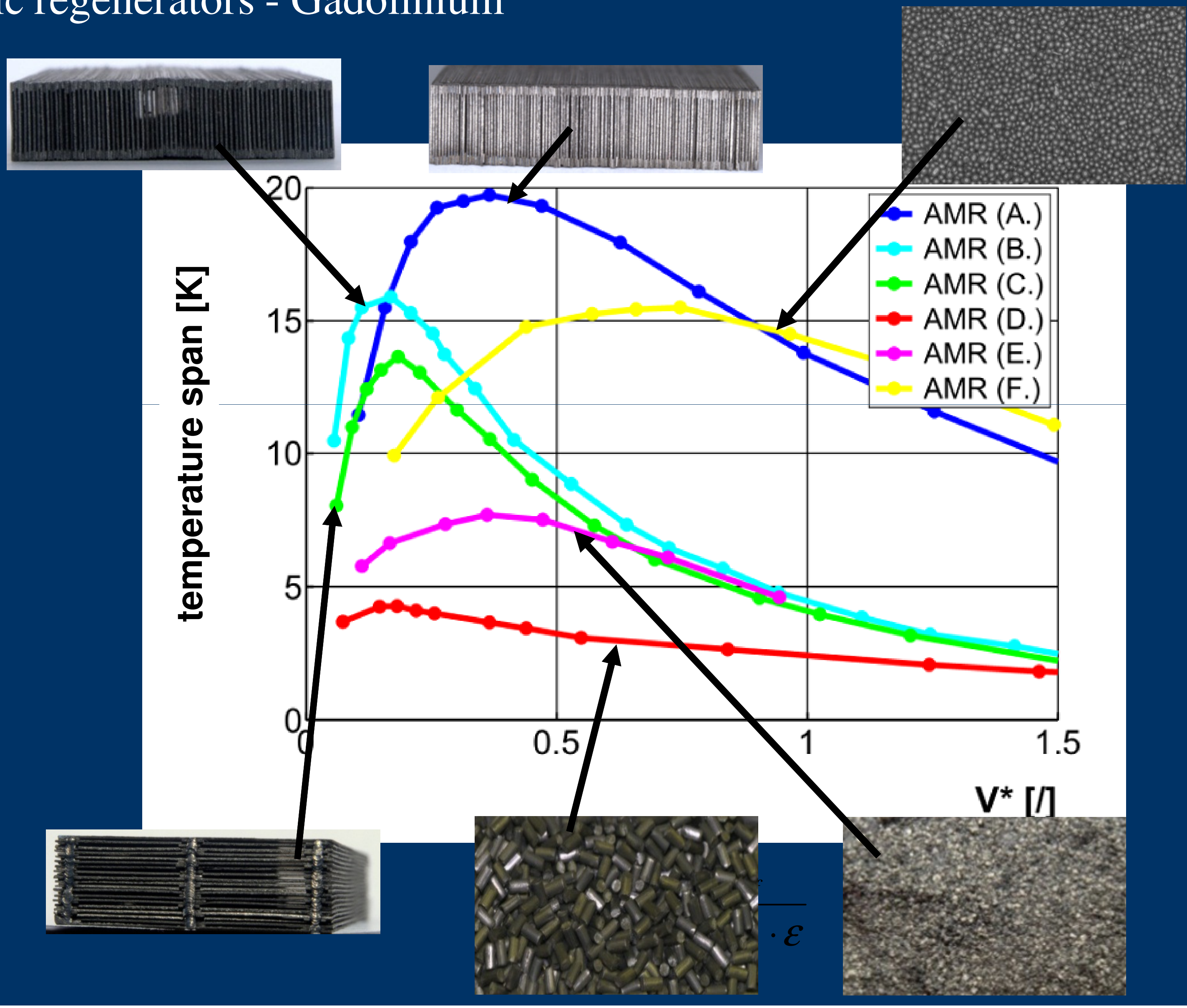




Tusek et al, Applied Thermal Engineering 53 (2013) 57-66

Experimental work

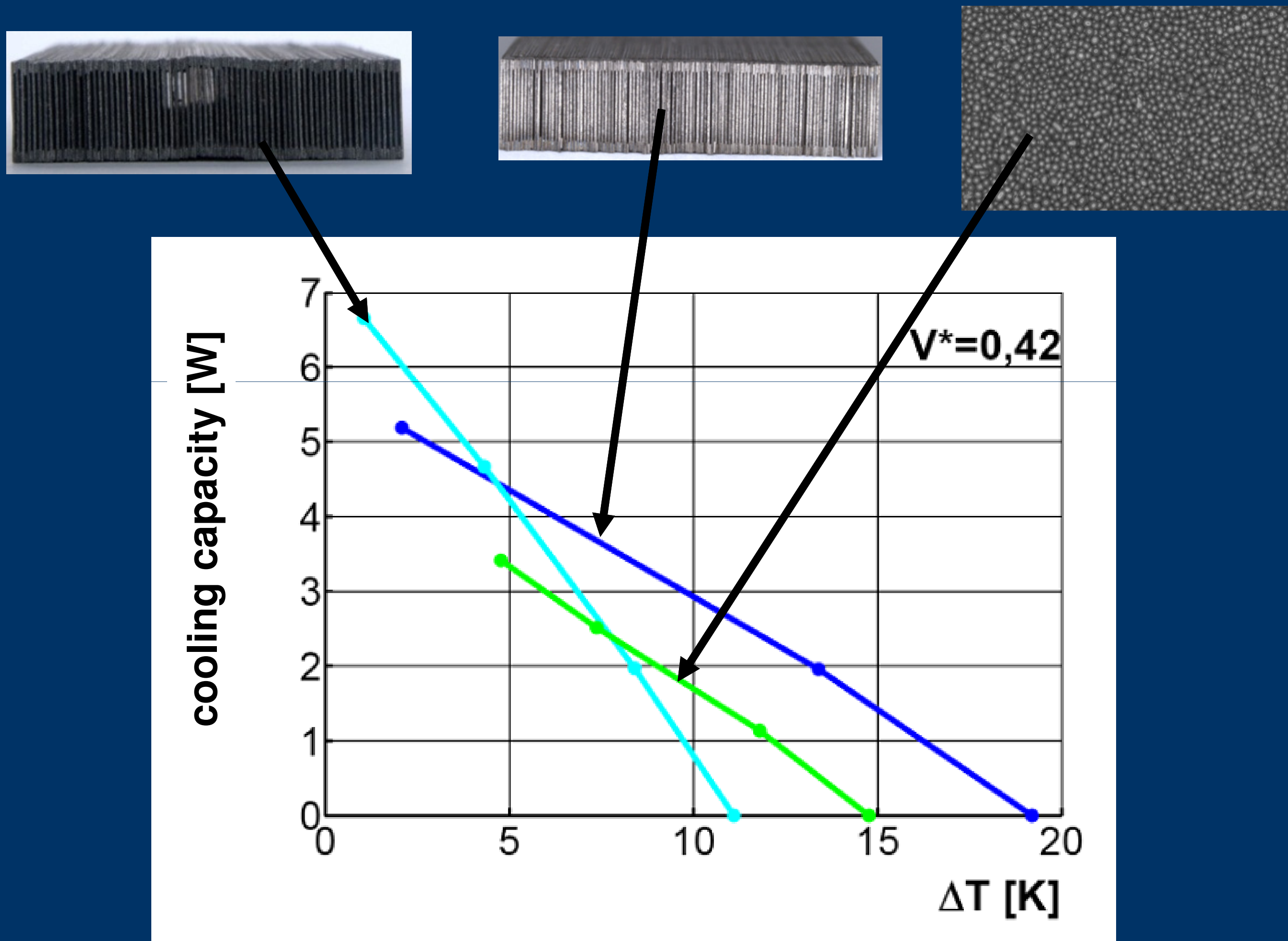
Magnetocaloric regenerators - Gadolinium



Tusek et al, Applied Thermal Engineering 53 (2013) 57-66

Experimental work

Magnetocaloric regenerators - Gadolinium



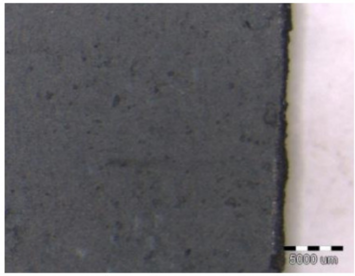
Tusek et al, Applied Thermal Engineering 53 (2013) 57-66

Experimental work

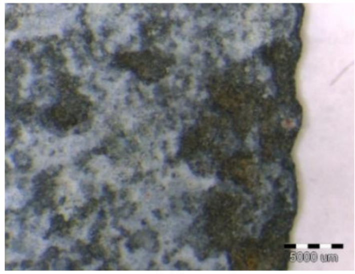
Magnetocaloric regenerators - Gadolinium

Geometry of analyzed AMRs.

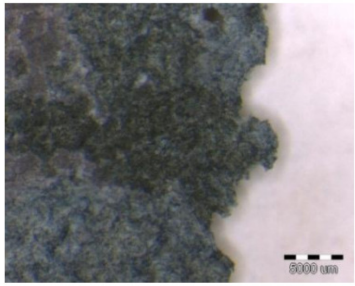
Outer dimensions [mm]	(A.)	(B.)	(C.)	(D.)	(E.)	(F.)
	10 (height) × 80 (length) × 39 (width)					
Material geometry	Plates; $t = 0.25$ mm	Plates; $t = 0.25$ mm	Plates; $t = 0.25$ mm	Cylinders; $d = 2.5$ mm; $L = 4$ mm	Powder; $d = 0.35–0.5$ mm	Spheres; $d = 0.35–0.5$ mm
Plate's distance [mm]	0.1	0.25	0.25	/	/	/
Total heat transfer area [m^2]	0.1395	0.0896	0.0806	0.0198	0.1650	0.2400
Total mass of Gd [kg]	0.1763	0.1309	0.1427	0.1205	0.0930	0.1350
Average porosity [/]	0.2564	0.4667	0.4247	0.4188	0.5515	0.3490
Hydraulic diameter($d_h = 4 \cdot V_{AMR} \cdot \varepsilon / A_{ht}$) [mm]	0.2	0.5	0.5	2.22	0.3510	0.1530



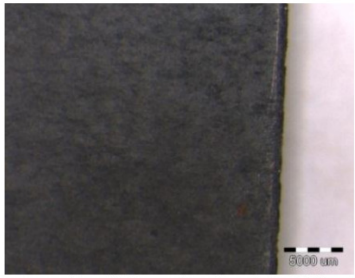
a.) referenčni vzorec



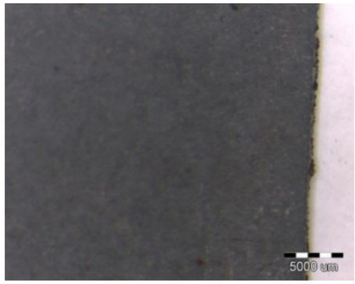
b.) voda



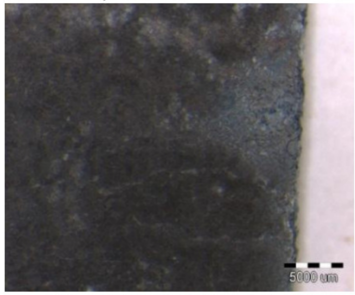
c.) destilirana voda



d.) 5% raztopine NaOH + 95% destil. vode



e.) 33% hladilne tekočine + 67% destil. vode



f.) 10% hladilne tekočine + 90% destil. vode

Tusek et al, Applied Thermal Engineering 53 (2013) 57-66

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Experimental work

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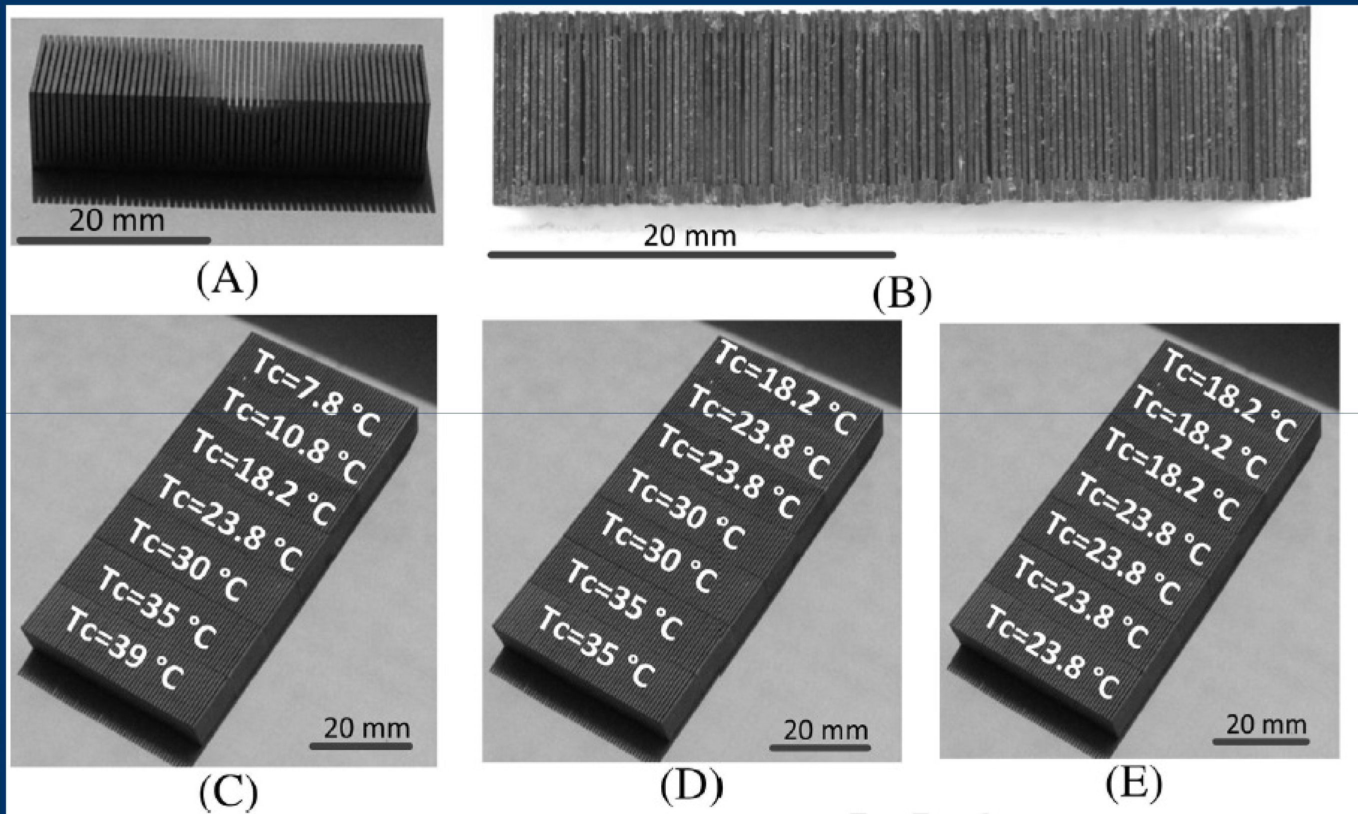
Magnetocaloric regenerators - LaFeSiCo



Photographs of the evaluated AMRs (single LaFe13 L x L yCoxSiy layer (A.); laser-welded Gd-based AMR (B.); seven layered La-based AMR (C.); four-layered La-based AMR (D.) and two-layered La-based AMR (E.))

Tusek, J., et al., Experimental comparison of multi-layered LaFeCoSi and single-layered Gd active magnetic regenerators for use in a room-temperature magnetic refrigerator, International Journal of Refrigeration(2013)

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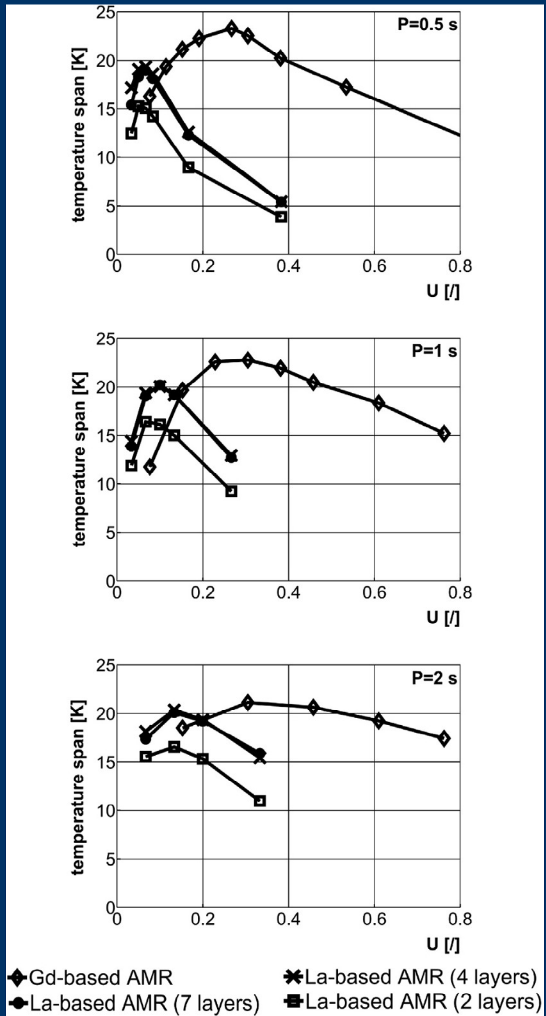
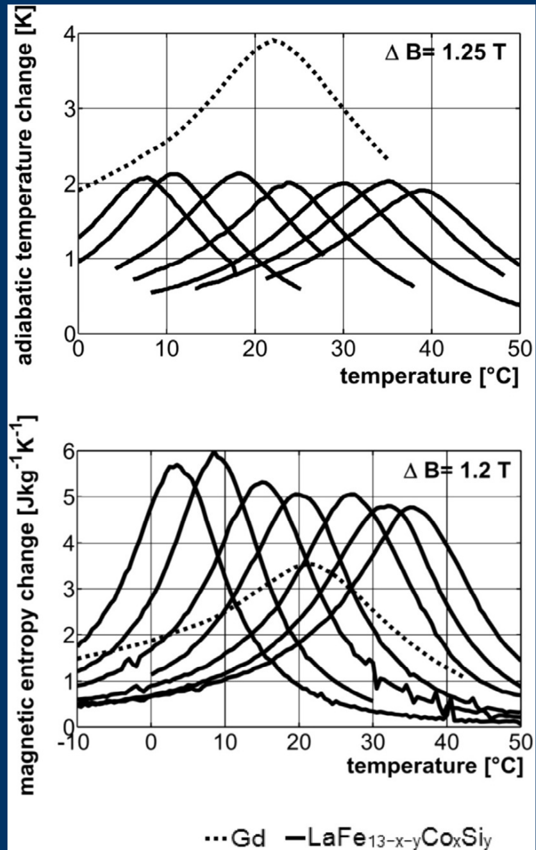
Experimental work

Magnetocaloric regenerators - LaFeSiCo

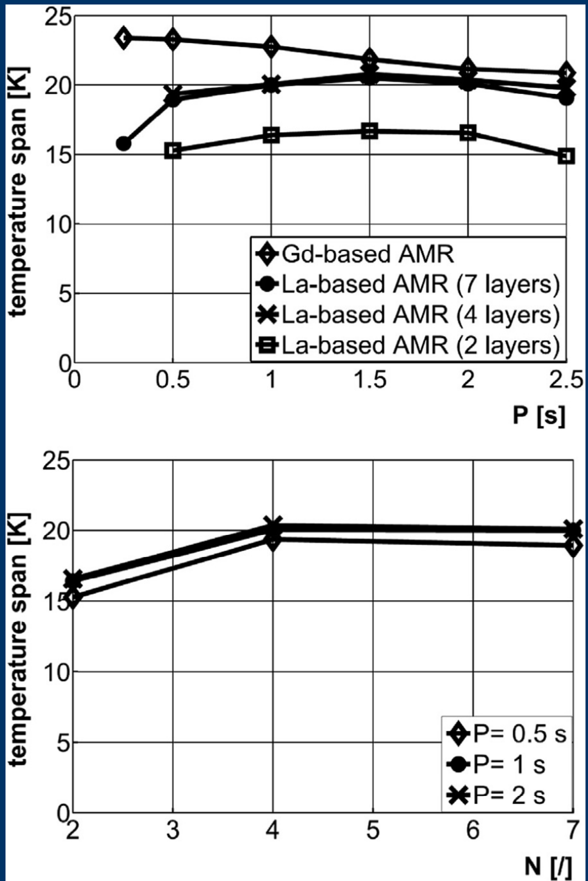


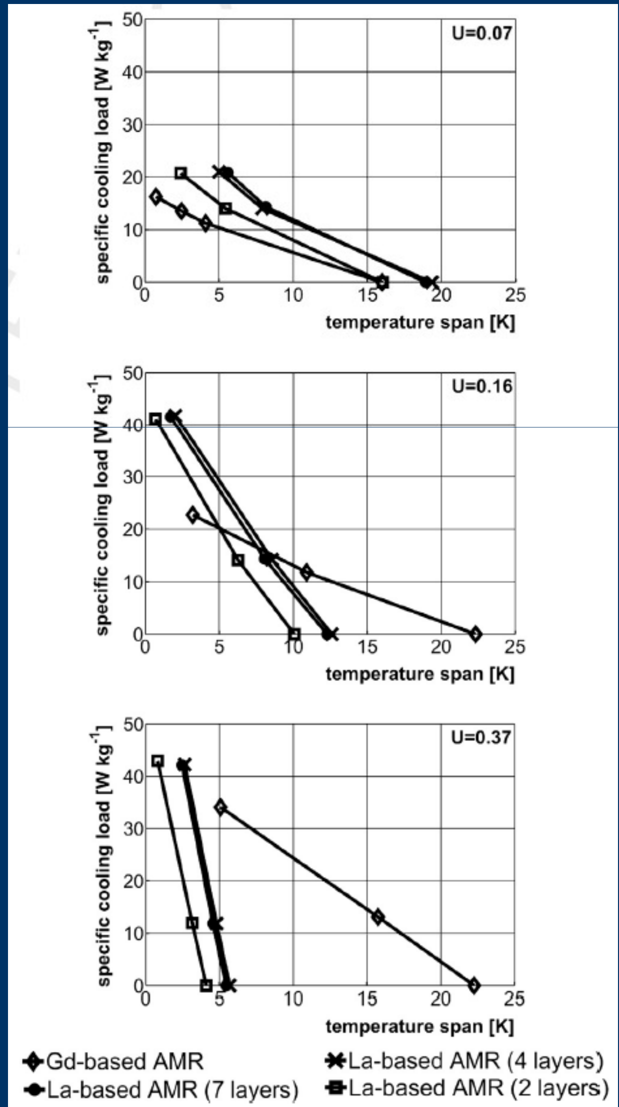


Tusek, J., et al., Experimental comparison of multi-layered LaFeCoSi and single-layered Gd active magnetic regenerators for use in a room-temperature magnetic refrigerator, International Journal of Refrigeration(2013)

Experimental work

Magnetocaloric regenerators - LaFeSiCo



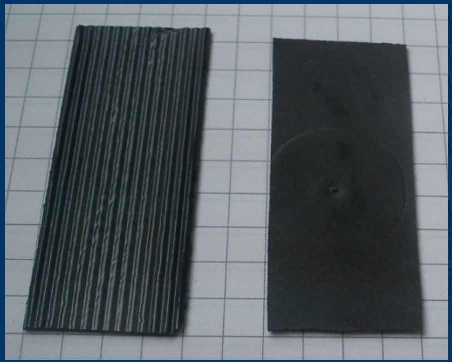


Tusek, J., et al., Experimental comparison of multi-layered LaFeCoSi and single-layered Gd active magnetic regenerators for use in a room-temperature magnetic refrigerator, International Journal of Refrigeration(2013)

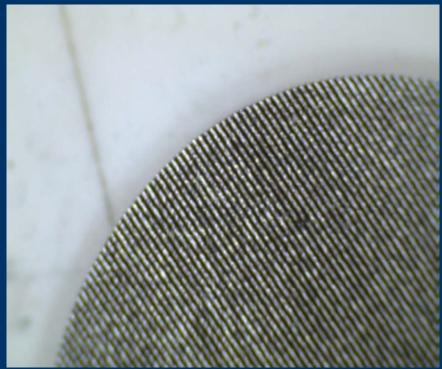
Experimental work

Magnetocaloric regenerators – processing experience

Laser welding***
Laser driling, cutting
Different epoxy based structures and methods



Samples of pressed, corrugated, and flat "elastic" plates with thickness of 0.3 mm Based on LaFeCoSi powders.



Laser drilled – channels 150 microns

***Patent application: TUŠEK, Jaka, POMPE, Klemen, KITANOVSKI, Andrej, TUŠEK, Janez, POREDOŠ, Alojz. *A method for producing an active magnetic regenerator*. Munich: European Patent Office, 2013.

Electrocaloric Refrigeration at UL since 2011

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WHAT WE DO

- Numerical simulations on regenerators, thermodynamic cycles, (Matlab)
- Experimental tests on regenerators
- Conceptual designs & Prototyping

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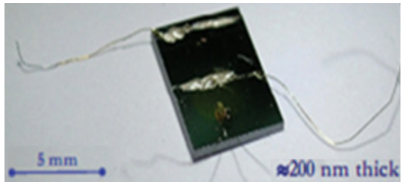
REVIEW OF KNOWN MATERIALS

List of electrocaloric materials (all are electrical insulators !):

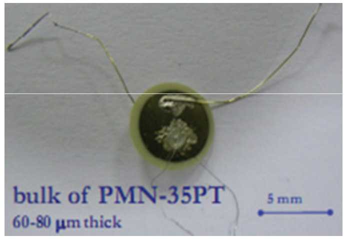


- ***ceramic thin films*** (BV ~ 200 MV/m)
  - PZT ($Pb[Zr_xTi_{1-x}]O_3$) 0<x<1 x=molar ratio
  - PLZT ($Pb_{1-x}La_x[Zr_zTi_{1-z}]_{1-x/4}O_3$),
  - PST ($Pb[Sc_xTa_{1-x}]O_3$)
  - BST ($[Ba_xSr_{1-x}]TiO_3$)
  - (1-x)PMN-PT(x) $(1-x)Pb[Mg_{1/3}Nb_{1/3}]O_3-(x)PbTiO_3$

- ***polymer thin films:***
  - copolymer (P(VDF-TrFE)) [polyvinylidene fluoride with trifluoroethylene]
  - terpolymer P(VDF-TrFE-CFE) [polyvinylidene fluoride with trifluoroethylene and chlorofluoroethylene]

- ***bulk ceramics*** (BV ~ 10 MV/m)
  - **same composition** as thin films,
  - $BaTiO_3$

- ***monocrystals*** (BV ~ 5 MV/m)
  - KH_2PO_4
  - PMN
  - NH_4HSO_4



See also Ozbolt et al, International Journal of Refrigeration 2013, Ozbolt et al, International journal of Refrigeration - submitted

Numerics and theoretical work

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Selection criteria:

- high ECE around room temperature
- plates with thickness of 100 µm

PLAZNIK,et al,. Numerical study of an electrocaloric cooling device. European Conference on Materials and Technologies for Sustainable Growth, Bled, 19. -21, September 201.

1. case scenario

- **BULK MATERIAL**

  - PMN ceramics [3]

ΔT_{ad} (ΔE=9 MV/m)	2.5 K
ρ	7800 kg·m^{-3}
c_E	310 J·kg^{-1}K^{-1}

STATE OF THE ART

2. case scenario

- **THIN FILM MULTILAYER CAPACITOR**

  - P(VDF-TrFE-CFE) Terpolymer [4]

ΔTad (ΔE=100MV/m)	7 K
ρ	1800 kg·m^{-3}
c_E	1700 J·kg^{-1}K^{-1}

NOT YET AVALIABLE

NEED FOR POSTPROCESSING !

[3] B. Rožič et al., Ferroelectrics, 2010. 405: 26-31.
[4] Li, X., et al., Applied Physics Letters, 2011. 99(5): 052907-052910.

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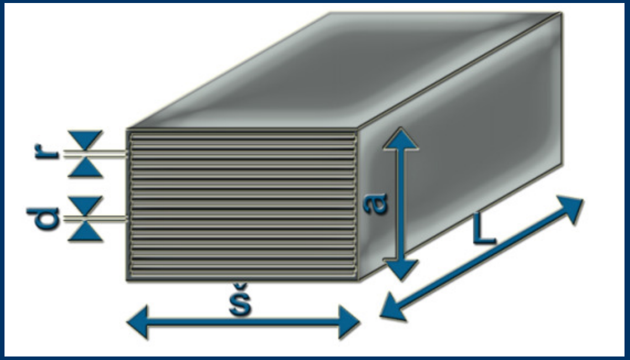
Numerics and theoretical work

- Geometrical properties of the regenerators

L –length	150 mm
A –height	10 mm
Š –width	50 mm
r – fluid channel height	0,05 mm
d – plate thickness	0,1 mm



- Working fluid – silicon oil – required replacement for heat transfer fluid

- Operation conditions:

  - temperature span of 20 K
  - 4 frequencies: 0.5 Hz, 1 Hz, 1.5 Hz, 2 Hz
  - variation of mass flow rate expressed by:

$$V^* = \frac{\text{volum of pumped fluid through the regenerator}}{\text{volume of the fluid in the regenerator}}$$

PLAZNIK,et al,. Numerical study of an electrocaloric cooling device. European Conference on Materials and Technologies for Sustainable Growth, Bled, 19. -21, September 2013.

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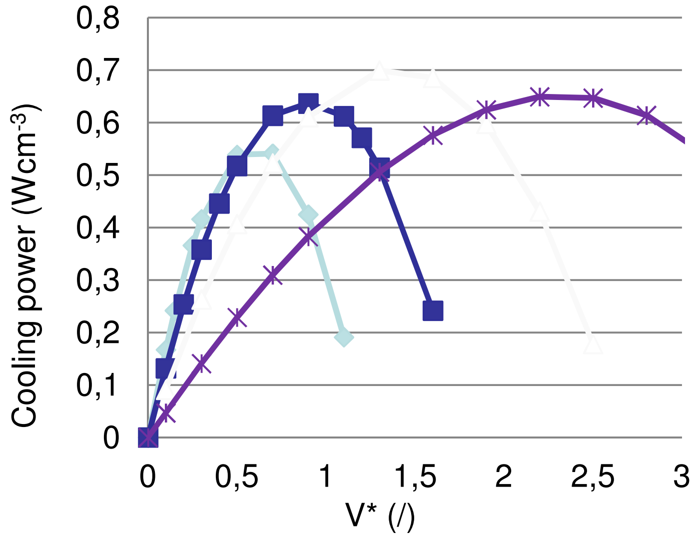
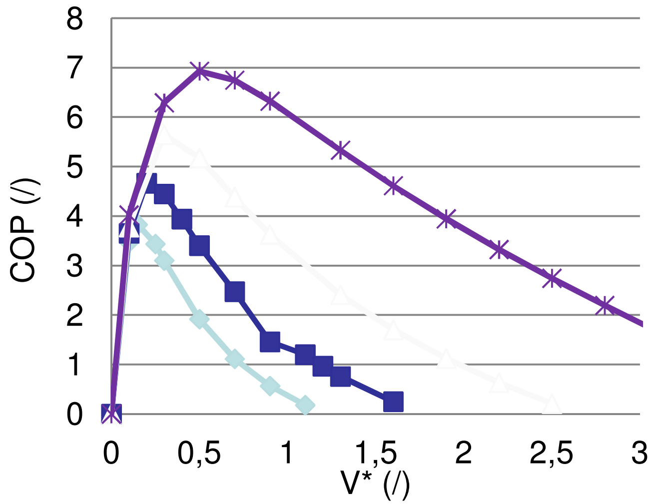
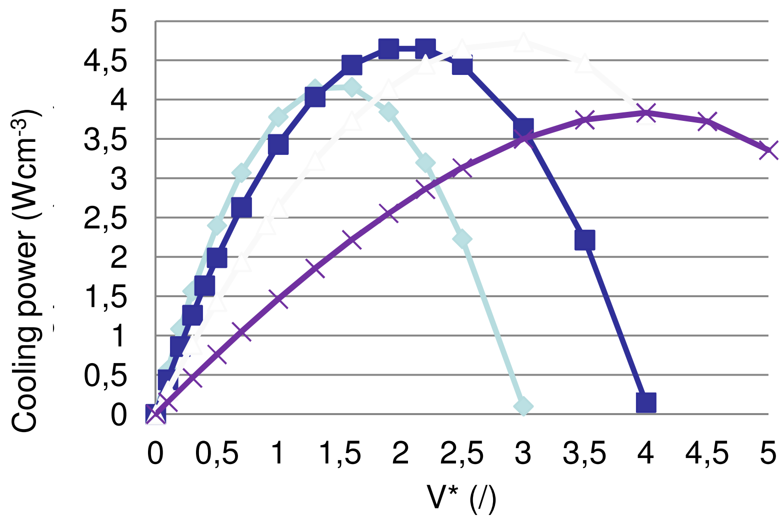
Numerics and theoretical work

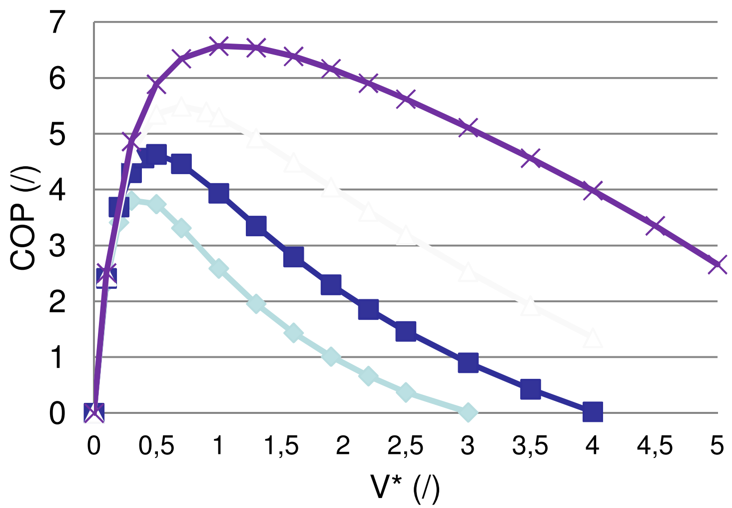
1. case scenario – **PMN ceramics**





2. case scenario - **MULTILAYER CAPACITOR**





f=2 Hz f= 1.5 Hz f=1 Hz f=0.5 Hz

PLAZNIK,et al,. Numerical study of an electrocaloric cooling device. European Conference on Materials and Technologies for Sustainable Growth, Bled, 19. -21, September 201.

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Numerics and theoretical work

Specifications of desired electrocaloric cooling device:

-50 W cooling power

-20 K temperature span

-COP=7

1. case scenario - state of the art electrocaloric plate

$$V_{material} = \frac{\dot{Q}_c}{\dot{q}_c} = \frac{50W}{0.23W\,/\,cm^3} = 217.5cm^3$$

$$V_{regenerator} = \frac{V_{material}}{1-\varepsilon} = \frac{217.5\text{cm}^3}{2/3} = 325\ \text{cm}^3$$

regenerator geometrical properties →

L=15 cm
h=1 cm
B=21.5 cm

2. case scenario – future electrocaloric plate

$$V_{material} = \frac{\dot{Q}_c}{\dot{q}_c} = \frac{50W}{1.45W\,/\,cm^3} = 34.5cm^3$$

$$V_{regenerator} = \frac{V_{material}}{1-\varepsilon} = \frac{34.5\ \text{cm}^3}{2/3} = 51.75\ \text{cm}^3$$

regenerator geometrical properties →

L=15 cm
h=1 cm
B=3 cm

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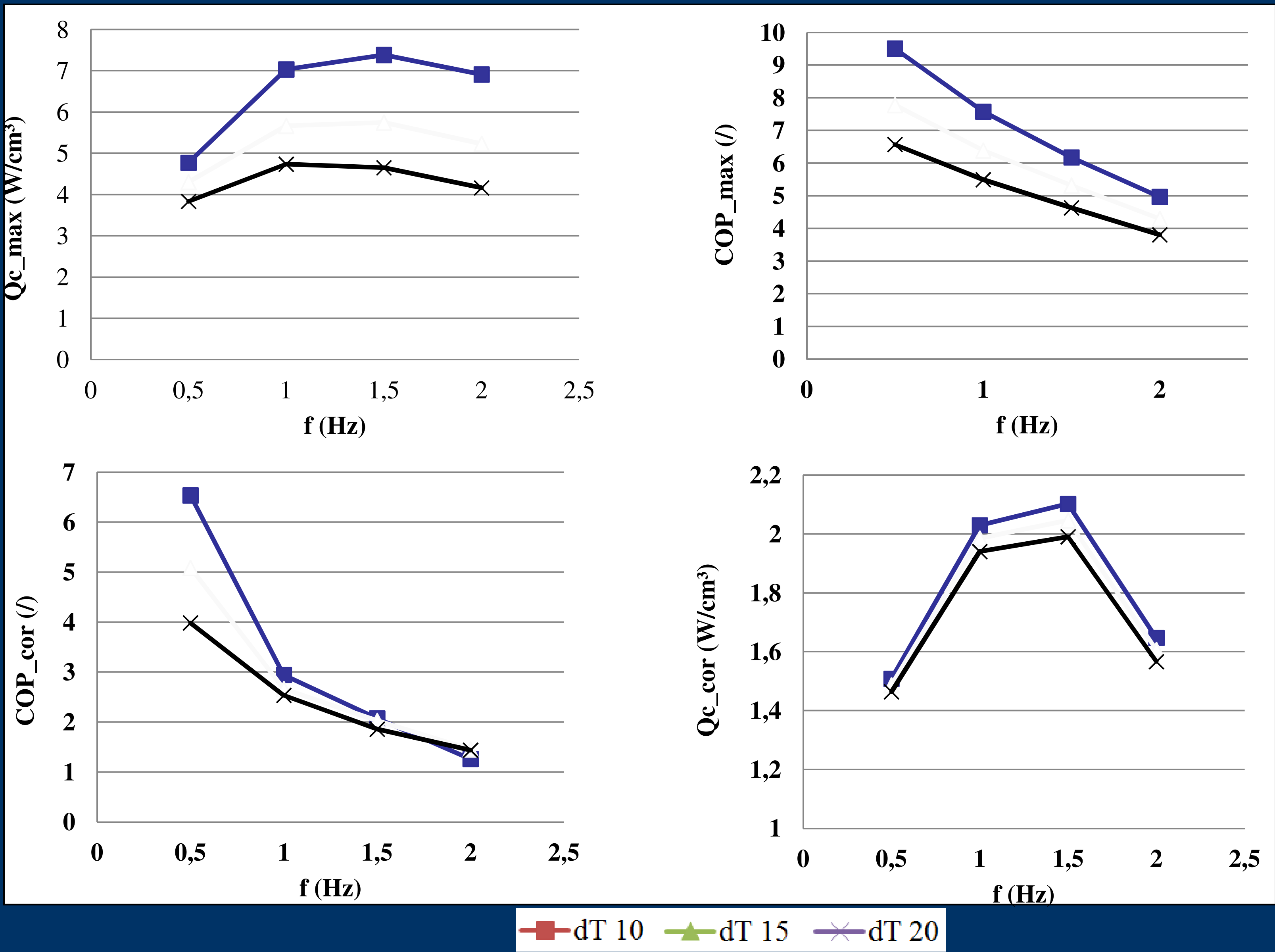
Numerics and theoretical work

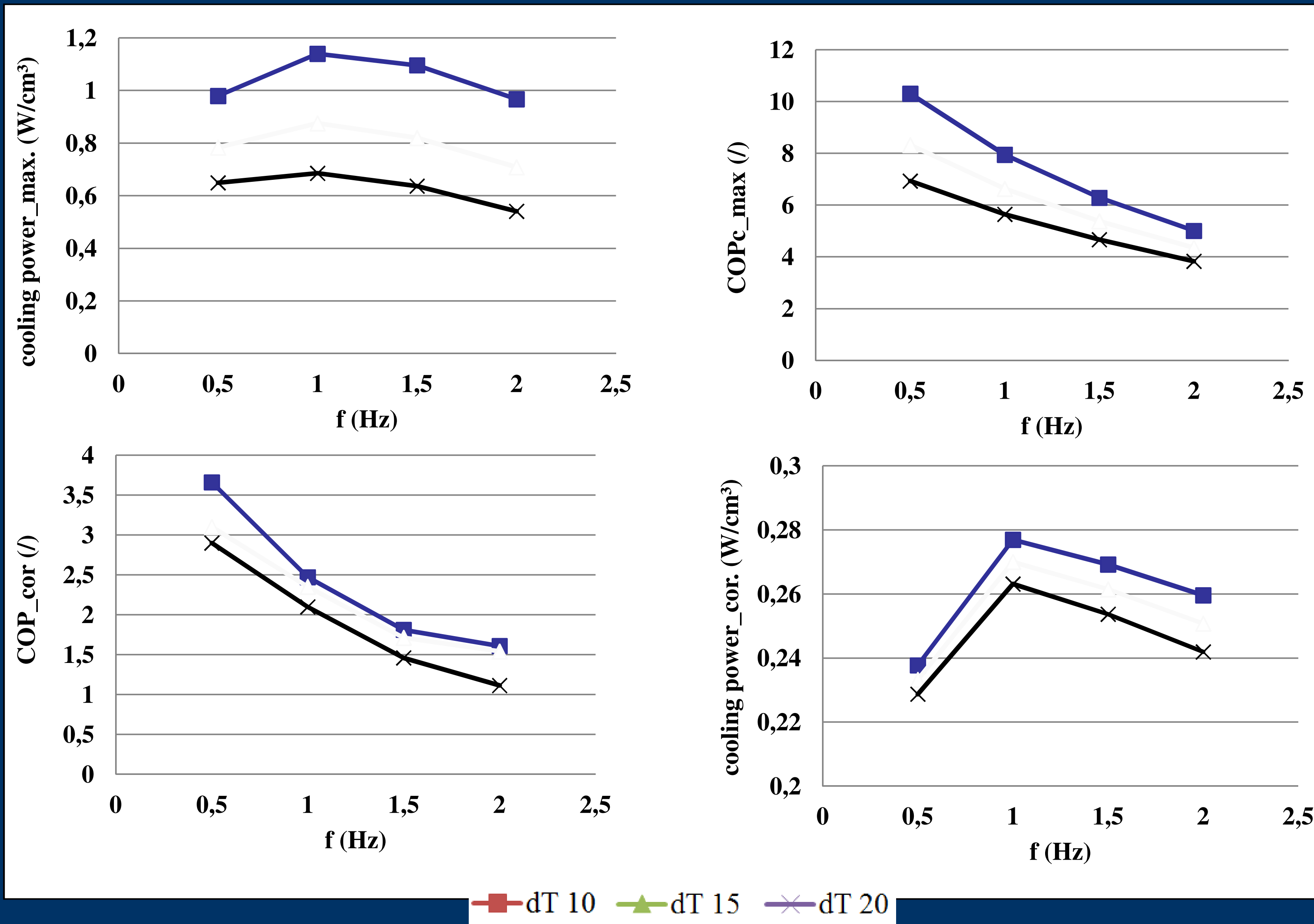
Multilayered



PLAZNIK,et al,. Numerical study of an electrocaloric cooling device. European Conference on Materials and Technologies for Sustainable Growth, Bled, 19. -21, September 201.

Numerics and theoretical work

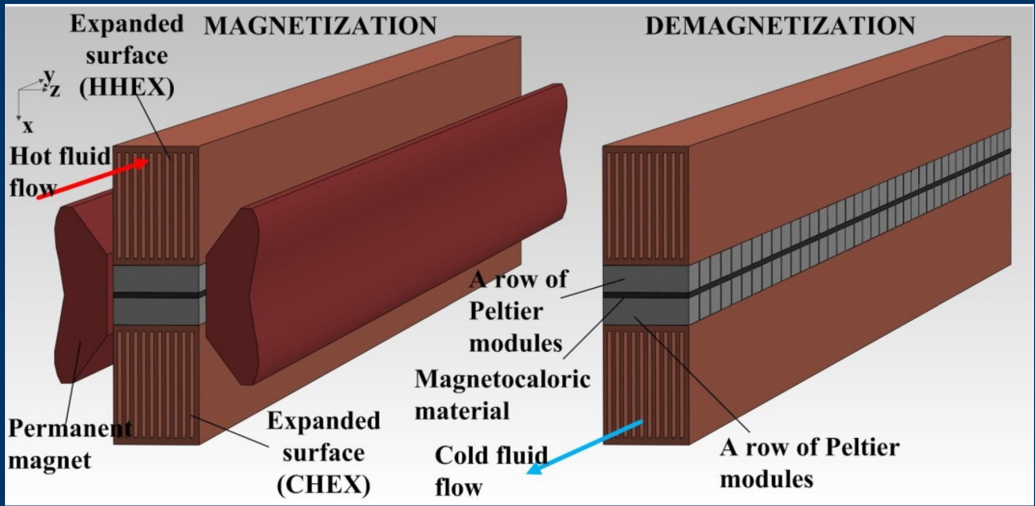
State of the art



PLAZNIK,et al,. Numerical study of an electrocaloric cooling device. European Conference on Materials and Technologies for Sustainable Growth, Bled, 19. -21, September 201.

Experimental work

Thermal diodes – application of thin film Peltier modules



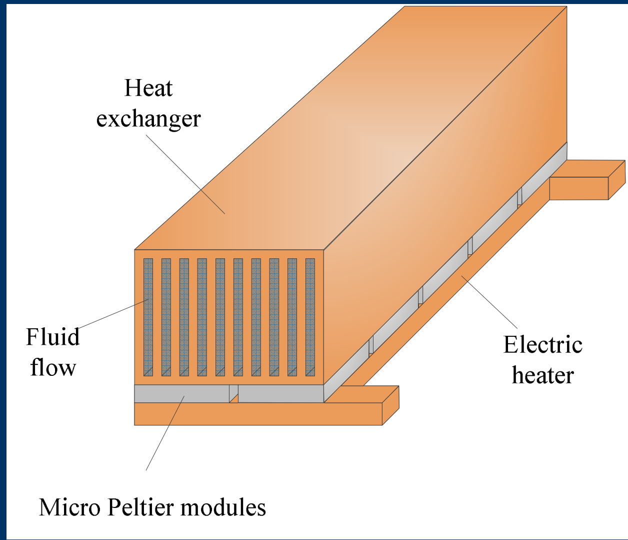
Thin-film Peltier modules. (i.e. Micropelt)

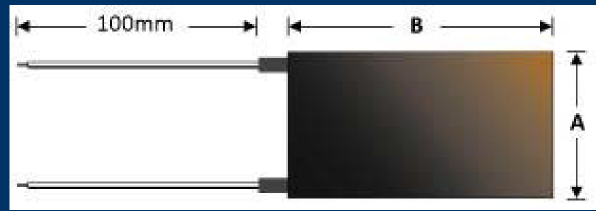
See Tomc, U., et al., A numerical comparison of a parallel-plate AMR and a magnetocaloric device with embodied micro thermoelectric thermal diodes, International Journal of Refrigeration (2013)

U. Tomc et al, Applied Thermal Engineering, Volume 58, Issues 1–2, September 2013, Pages 1-10

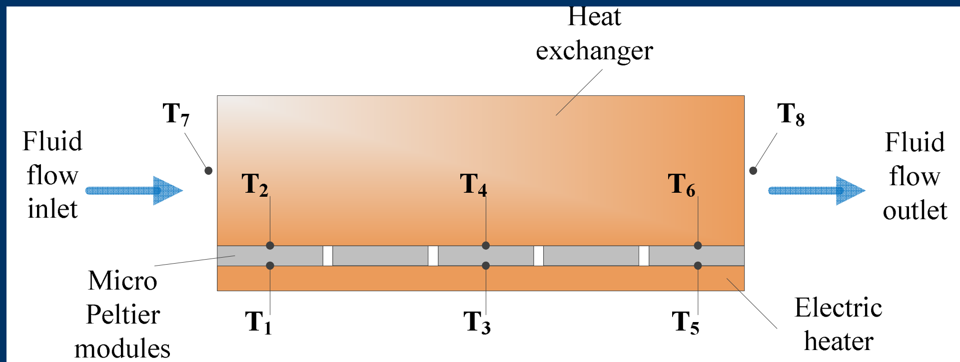
Experimental work

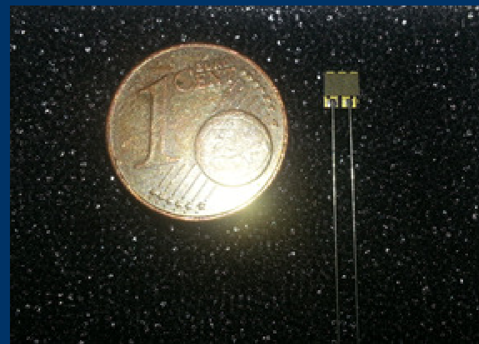
Thermal diodes – experimental device with thin film Peltier modules





Material	Polyimide
A	10 – 40 mm
B	10 – 40 mm
d	0.22 mm
q_{heater}	>0.8 W/cm²





Schematics of the experimental device.

U.Tomc, Work on the PhD Thesis, 2013

FUTURE WORK ??

- *MC with AMR – other fluids, special concepts of magnets and valve systems on existing prototypes*
- *MC with No AMR, Thermal diodes*
- *Electrocalorics (AER and No AER)*
- *Other solid state refrigeration alternatives*

LAHDE
LABORATORY FOR REFRIGERATION AND DISTRICT ENERGY

University *of Ljubljana*
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THANK YOU FOR YOUR ATTENTION

Delft Days on Magnetocalorics 2013
October 28-29 2013
Aula Congress Centre TU Delft, Mekelweg 2, Delft

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Delft University of Technology