THE PERFORMANCE OF A ROTARY ACTIVE MAGNETIC REFRIGERATOR

K. Engelbrecht, C.R.H. Bahl, K.K. Nielsen, D. Eriksen, R. Bjørk, A. Smith and N. Pryds

Electro-Functional Materials (EFM)
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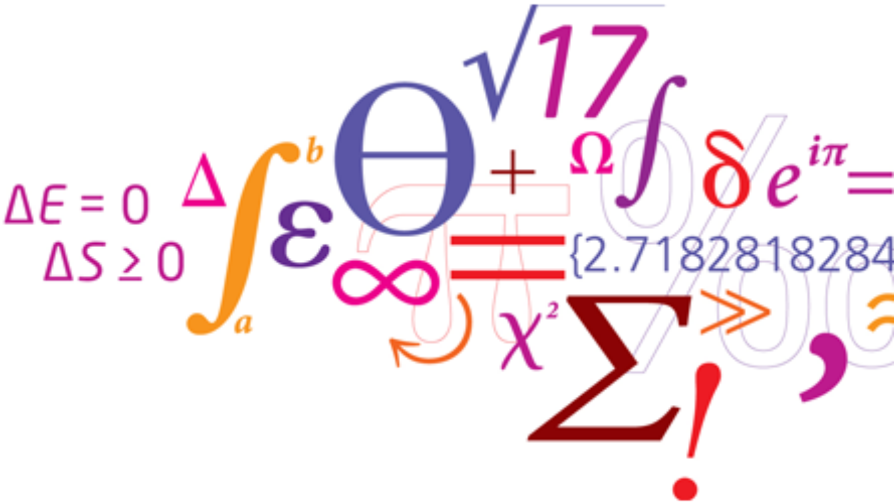
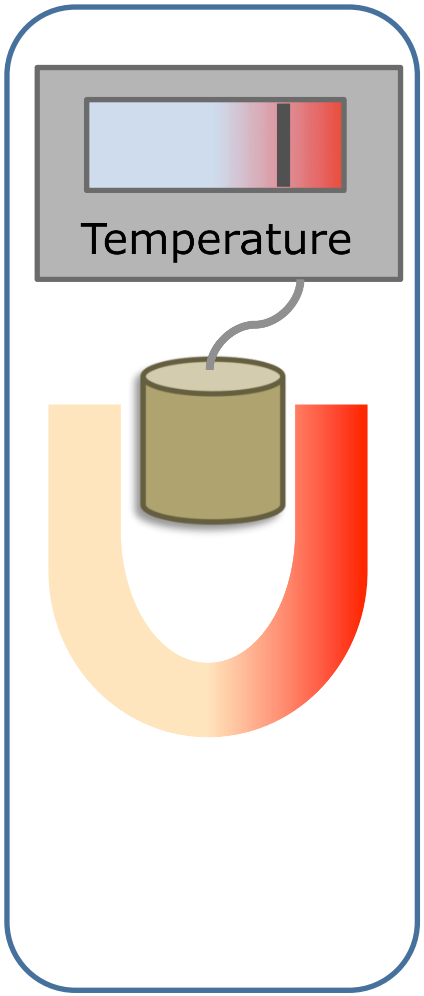
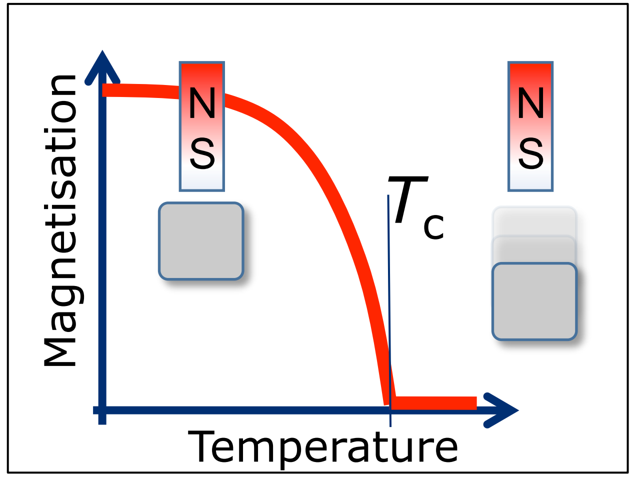
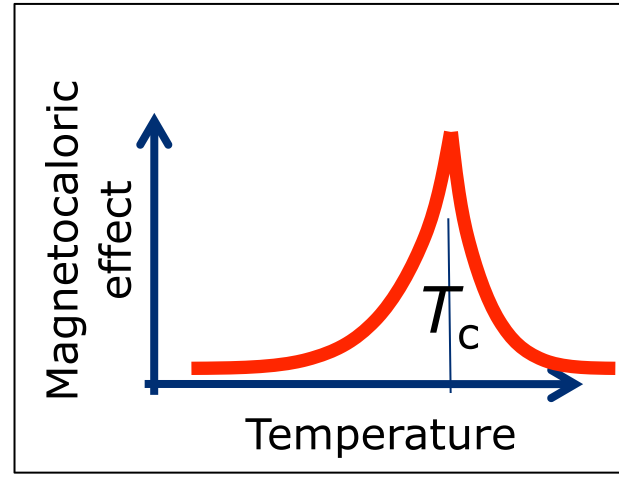


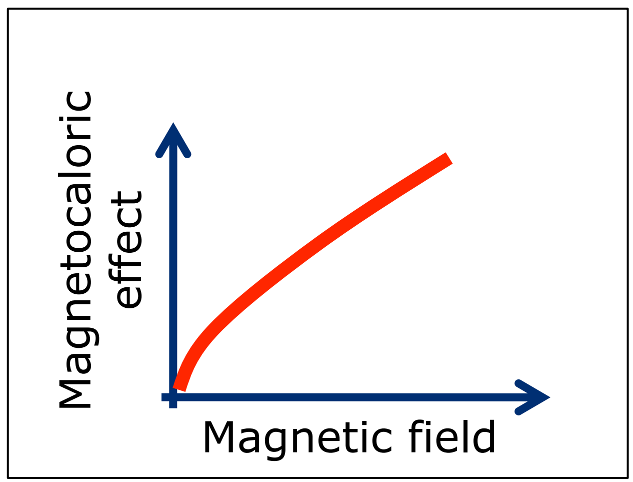
DTU Energy Conversion
Department of Energy Conversion and Storage

The magnetocaloric effect









↑ Magnetic field

↑ MCE

Who discovered the magnetocaloric effect?

The magnetocaloric effect, firstly discovered by Warbourg [1] in 1881, is the heating or cooling of magnetic materials subjected to magnetic field variation. The heating/cooling process through the magnetic field variation can be roughly

The magnetocaloric effect (MCE) was discovered in 1881 by Warburg.[1] It is the response of a magnetic solid to a

The MCE was discovered about 130 years ago [1],

Incidentally, the melanostibite mineral was found 10 years after the discovery of the magnetocaloric effect by Warburg in 1881 [18]. The magnetocaloric effect is related to the coupling

The magnetocaloric effect (MCE) is generally as the heating or the cooling of magnetic solids in a varying dc magnetic field. It was discovered by Warburg[1] an

The book is mainly devoted to the experimental results on the magnetocaloric effect (MCE) and influence of magnetic field on the entropy. MCE, discovered by Warburg in 1881 (Warburg 1881) in iron, displays itself in

Magnetic refrigeration is based on the magnetocaloric effect (MCE). The MCE, or adiabatic temperature change (ΔT_{ad}), which is detected as the heating or the cooling of magnetic materials due to a varying magnetic field, was originally discovered in iron by Warburg (1). The th

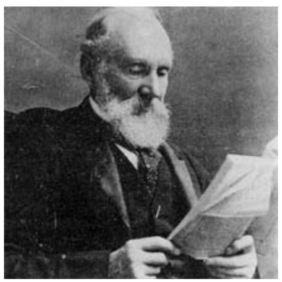
The magnetocaloric effect (MCE) is the reversible temperature change of a magnetic material upon the application or removal of a magnetic field. Its discovery is attributed to Warburg in 1881 (1), and it has been employed for achieving ultralow temperatures in research laboratories for

Who discovered the magnetocaloric effect?

- No, it wasn't Warburg!

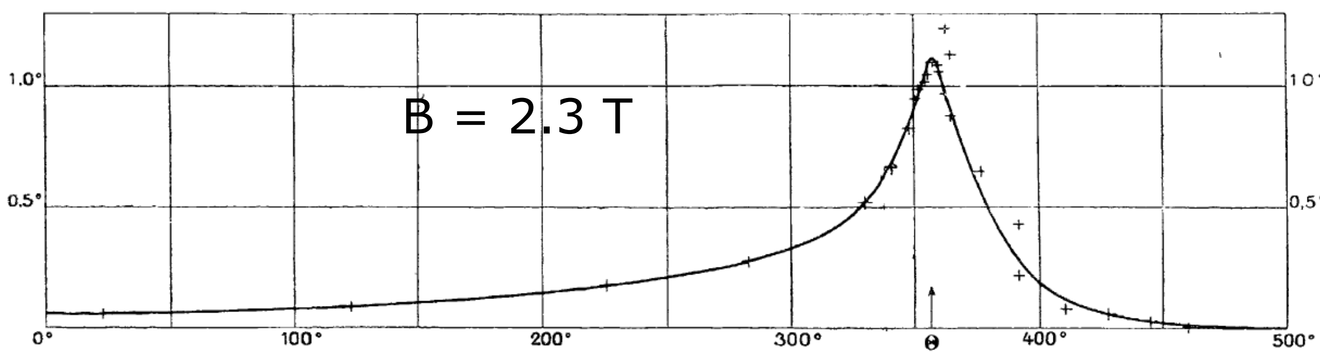
A. Smith: Who discovered the magnetocaloric effect? Eur. Phys. J. H **38**, 507-517 (2013)

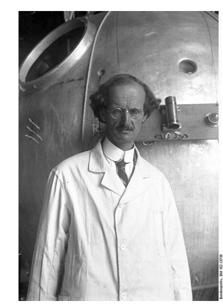
Thomson (1860): Theoretical prediction based on thermodynamics



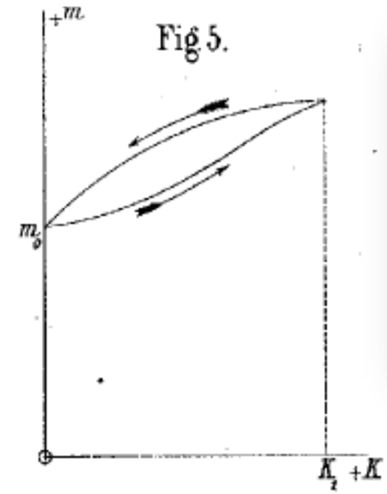
> rations when applied to these phenomena proves :—1. That a piece of soft iron at a moderate or low red heat, when drawn gently away from a magnet experiences a cooling effect, and when allowed to approach a magnet experiences a heating effect; that nickel at ordinary temperatures, and cobalt at

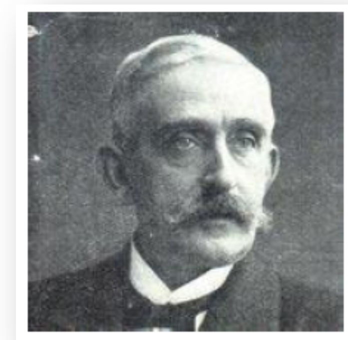
Weiss and Piccard (1917): Experimental discovery in nickel





(What did Warburg do?)





- Discovered hysteresis in iron
- Found Warburg's law:
  During a hysteresis loop an amount of heat equal to the area enclosed by the loop is dissipated in the magnetic body
- Used a small field, approx. 0.05 T:
  In iron at room temperature, the adiabatic temperature change for such a field is unmeasurably small
- Did not claim to discover the magnetocaloric effect
- Reported his results in a slightly confusing way (as a calculated equivalent temperature change in water)

…..one can express the hope that the moral of this story, well expressed by Simkin and Roychowdbury [Simkin 2003], will be better known: "Read before you cite!"

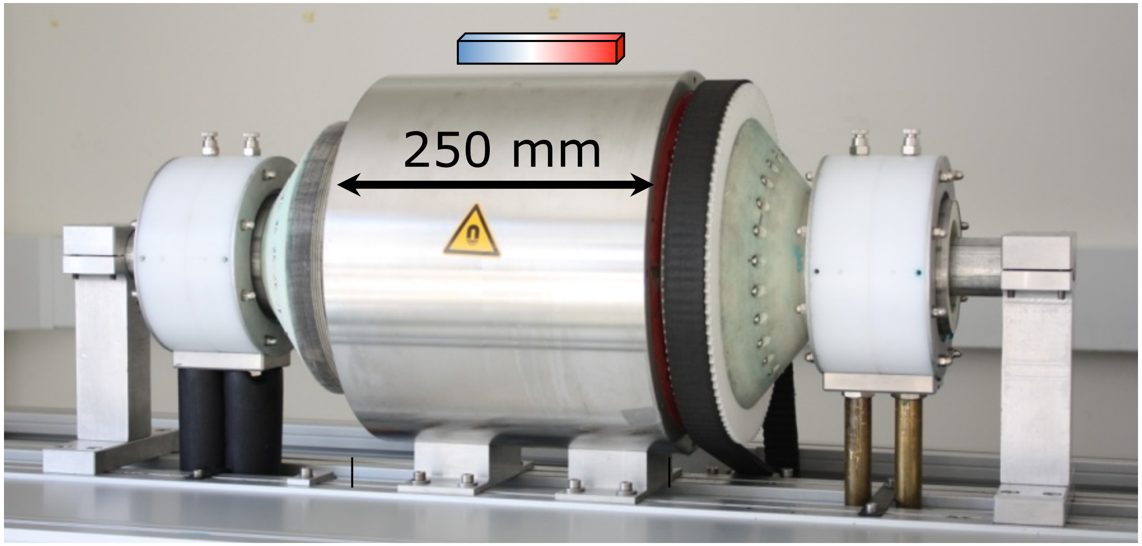
Why isn't it here yet? (What are the remaining challenges?)

- The magnetocaloric effect is quite small!
- Expensive parts are needed to for devices.
- Complex engineering issues in need to be solved.

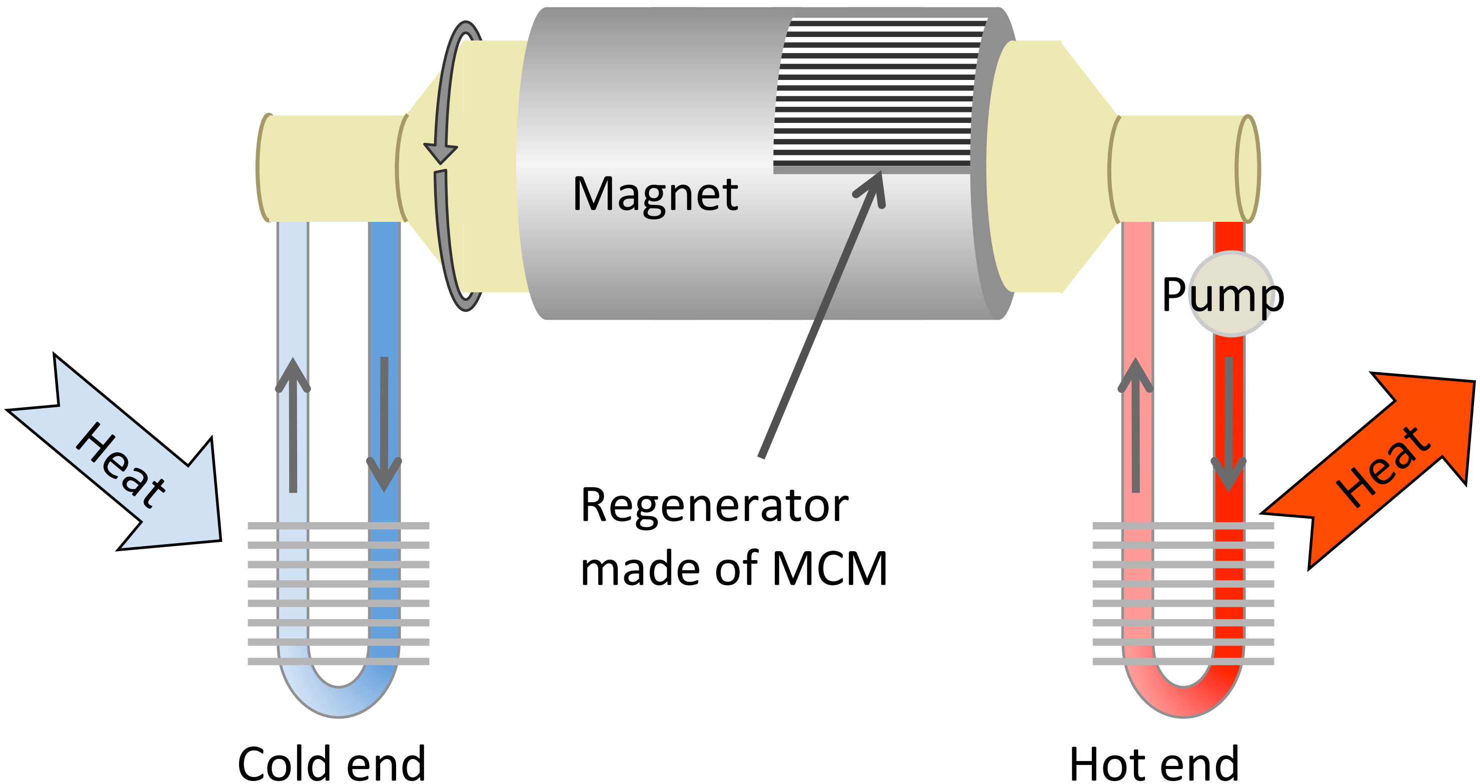
More work to do!

Rotary AMR at DTU

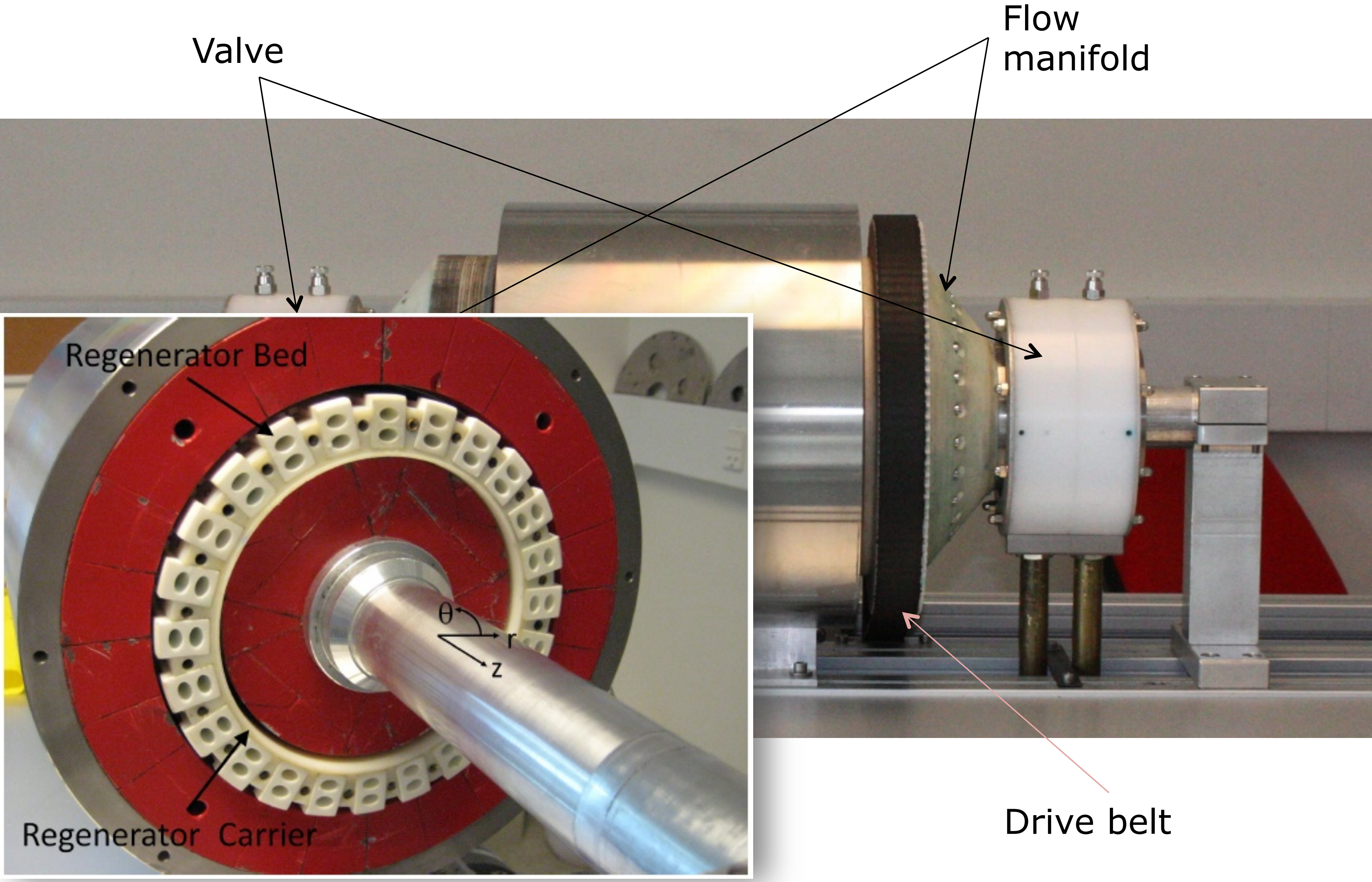
- 24 beds of Gd-spheres of 100 mm x 12.5 mm x 18.6 mm;
- 4-pole magnet with a magnetic field of 1.24 T;
- Mixture of 20% ethylene-glycol in deionised water;
- Volumetric flow rate measured at the cold end;
- Cooling power applied by an electric resistance.



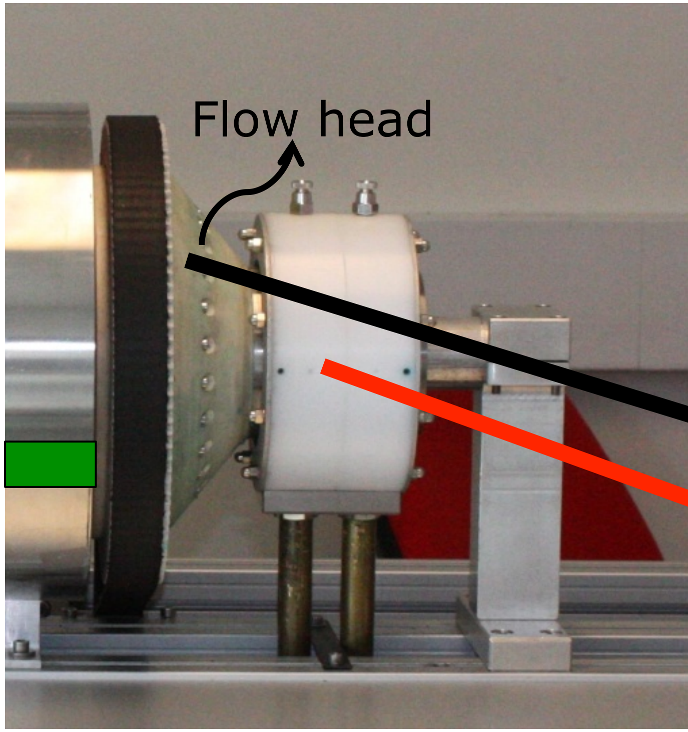
Flow system


Magnet
Pump
Heat
Heat
Regenerator
made of MCM
Cold end
Hot end

Our device


Valve
Flow
manifold
Regenerator Bed
θ
r
z
Regenerator Carrier
Drive belt

Flow distribution



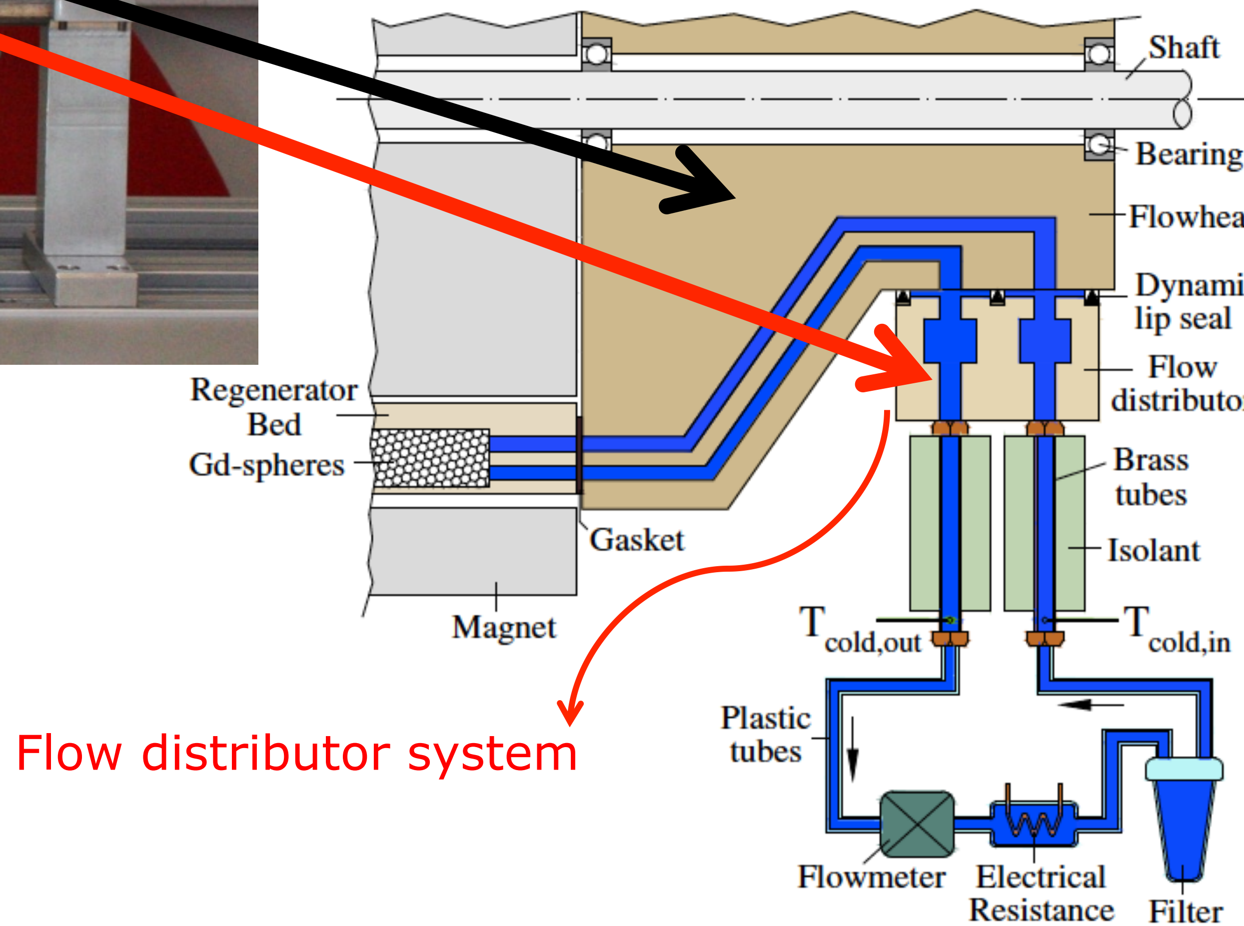
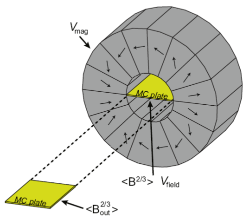


Fig. 1. Schematic representation of the cold end of the experimental device.

The optimal design of the magnet

Maximize Λ_{cool} for a given flux density

$$\Lambda_{\text{cool}} \equiv \left(\langle (\mu_0 H)^{2/3}_{\text{high}} \rangle - \langle (\mu_0 H)^{2/3}_{\text{low}} \rangle \right) \frac{V_{\text{field}}}{V_{\text{mag}}} P_{\text{field}}$$



- Use minimum amount of magnets
- Make the field volume as large as possible
- Utilize the magnet at all times
- Make sure the flux density in the low field region is low

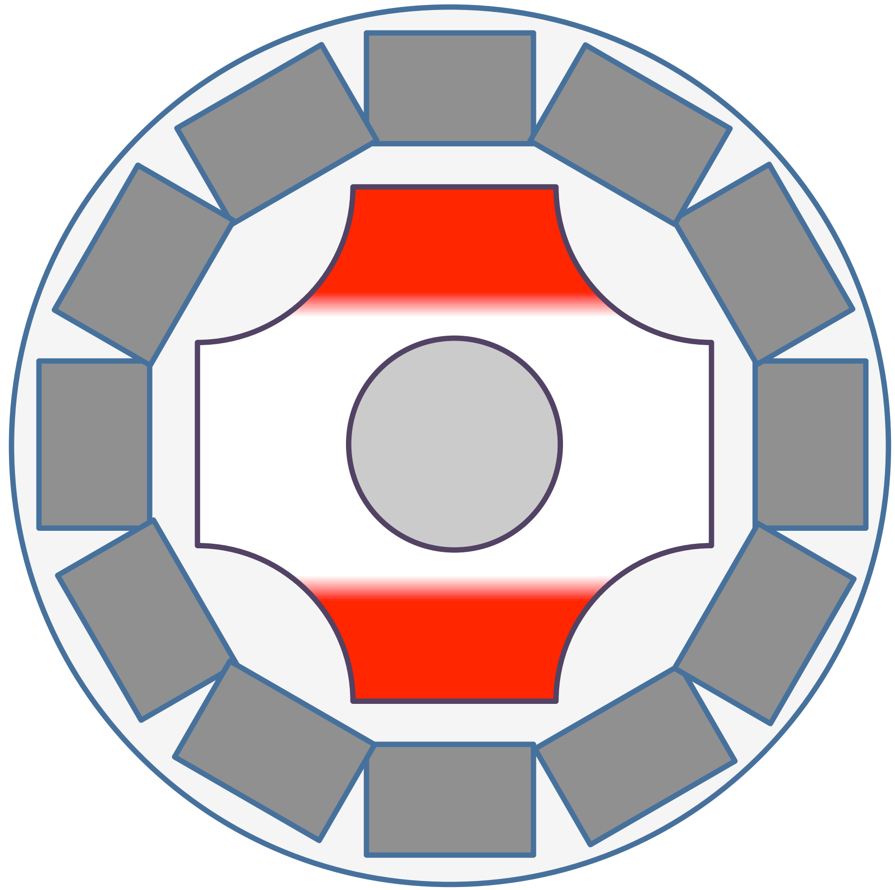
Bjørk, R., Bahl, C.R.H., Smith, A., Pryds, N.
Review and comparison of magnet designs for magnetic refrigeration
(2010) *International Journal of Refrigeration*, 33 (3), pp. 437-448.

Design constraints

- Continuous use of the magnetised volume and magnetocaloric material

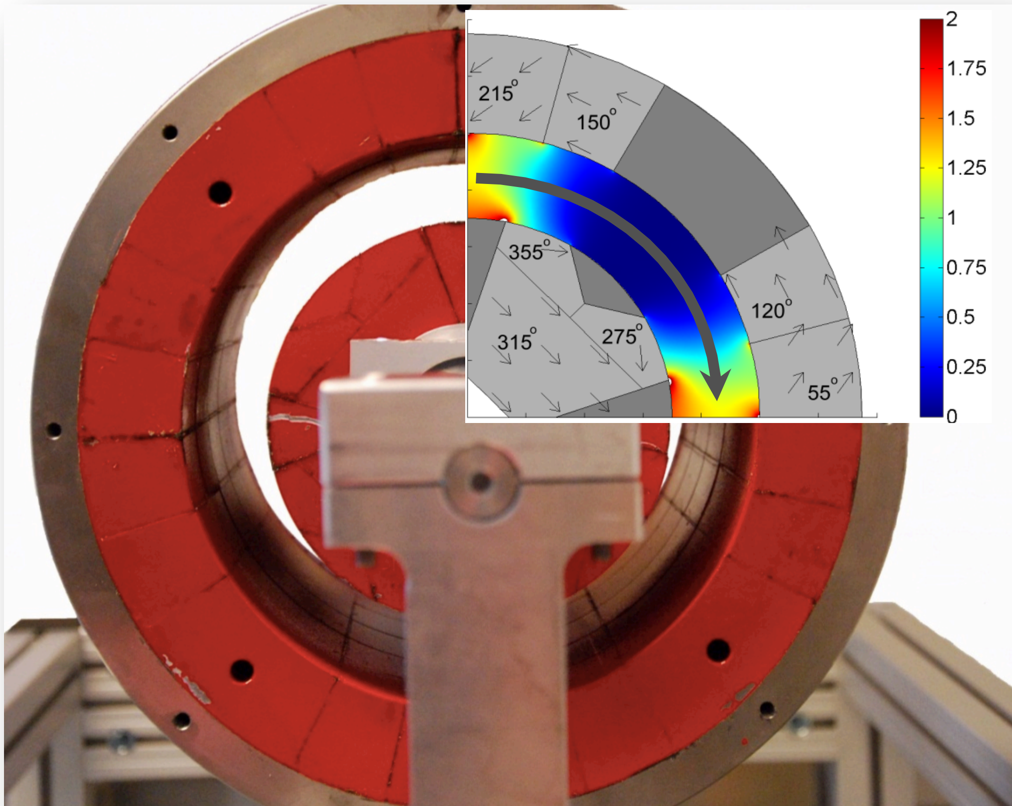
  As the magnetic flux is expensive to generate the magnetised regions should constantly be filled with magnetocaloric material that is constantly in use.

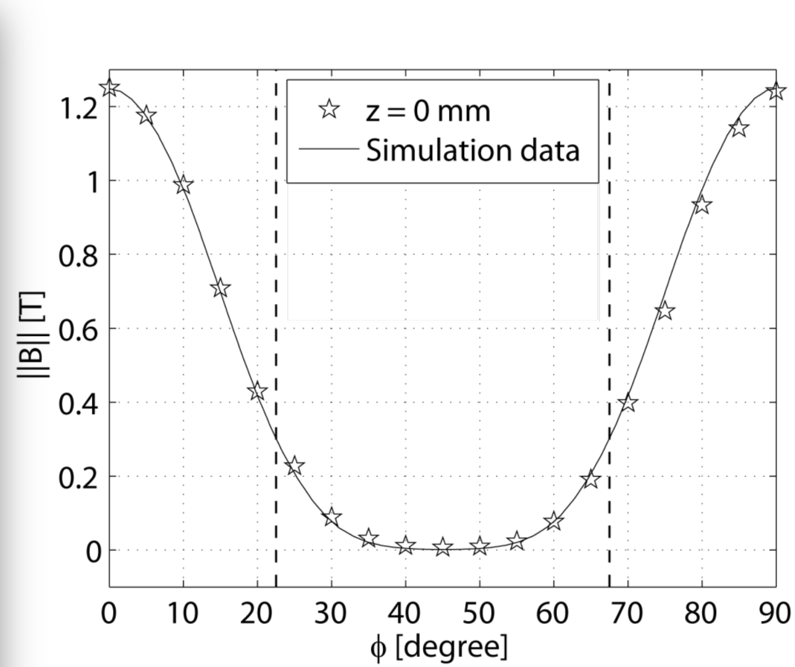
- Equal size of high and low field regions



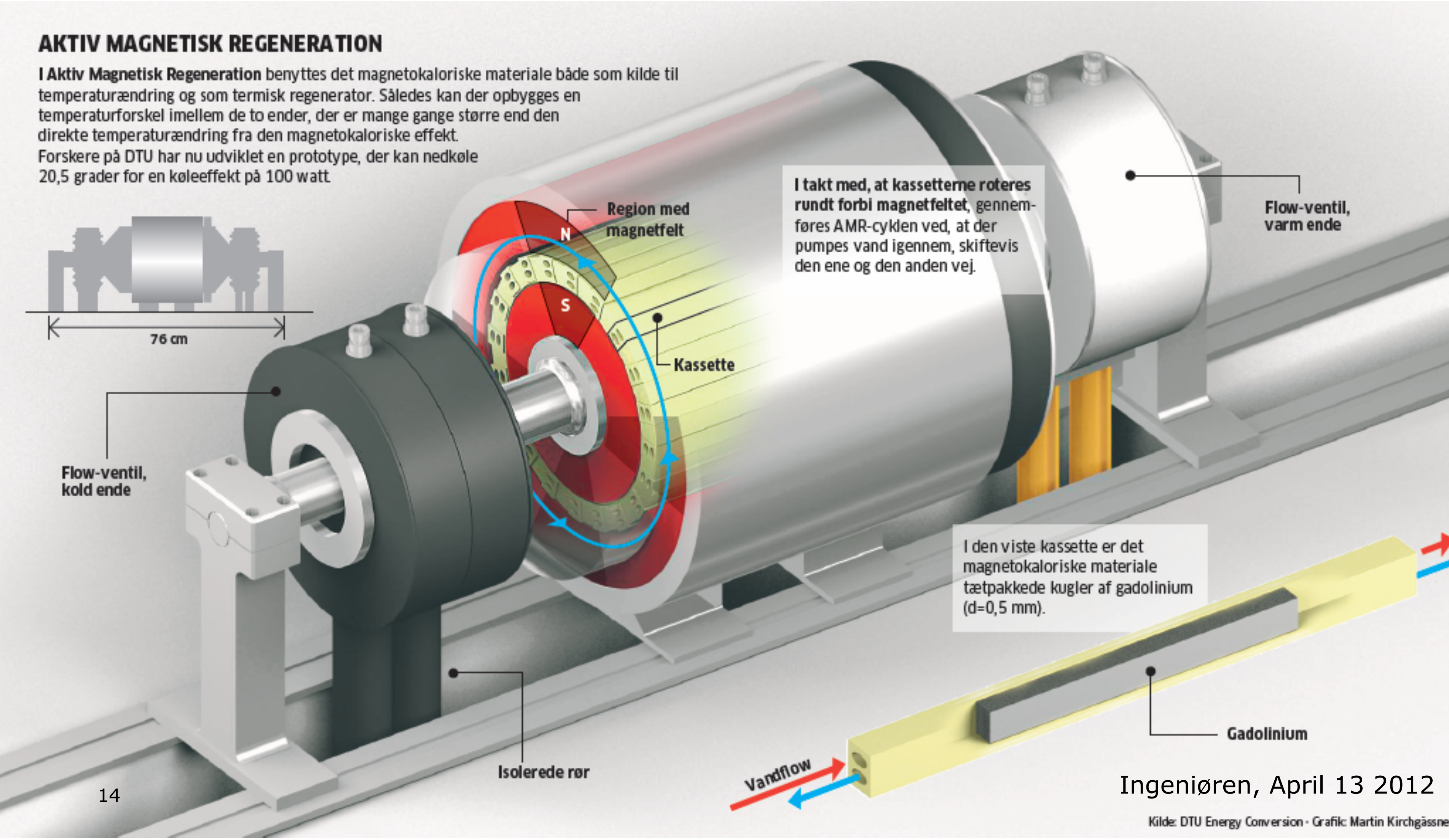
Design of a permanent magnet field source

- Good correspondence between numerical model and measured values.



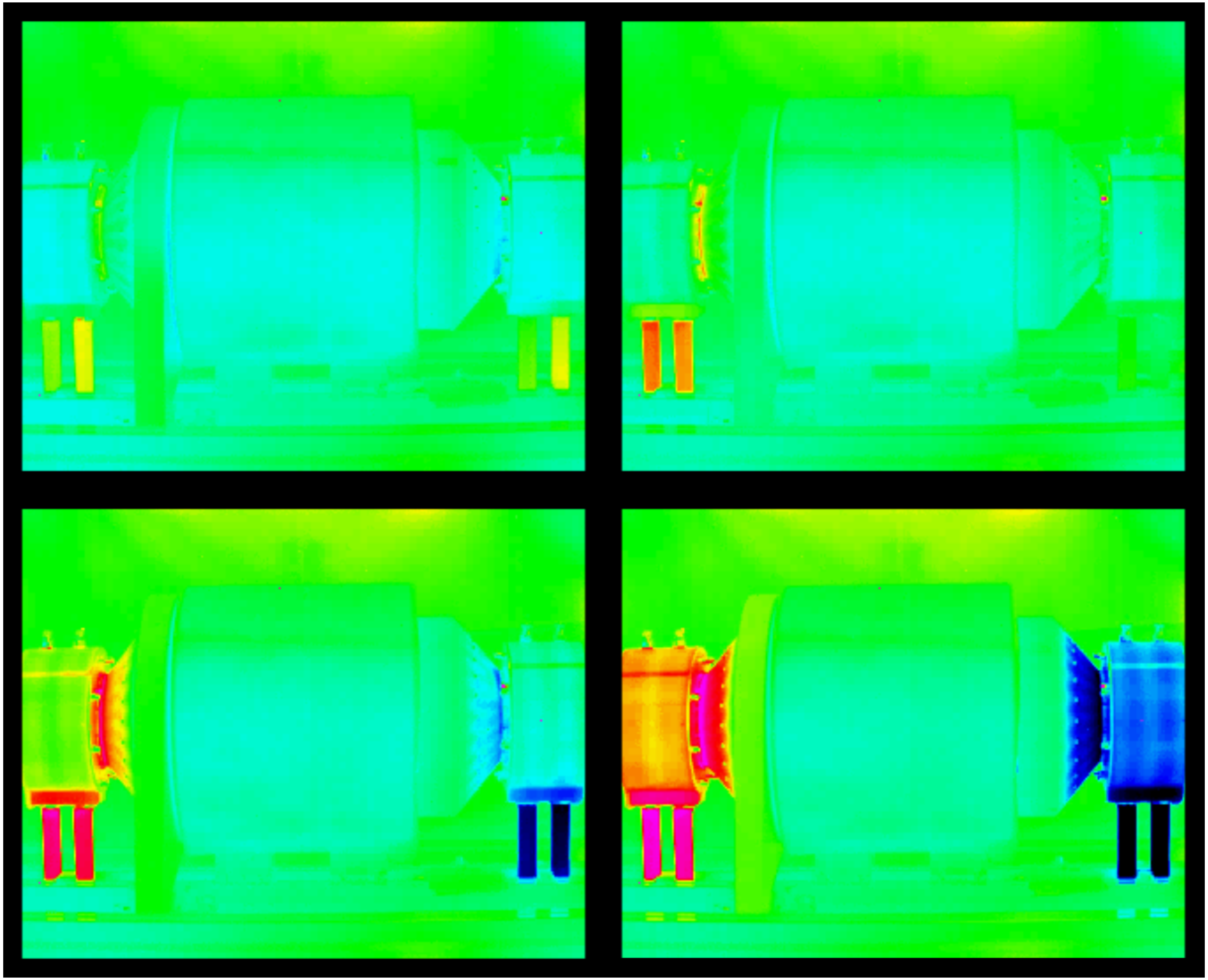


Prototype device

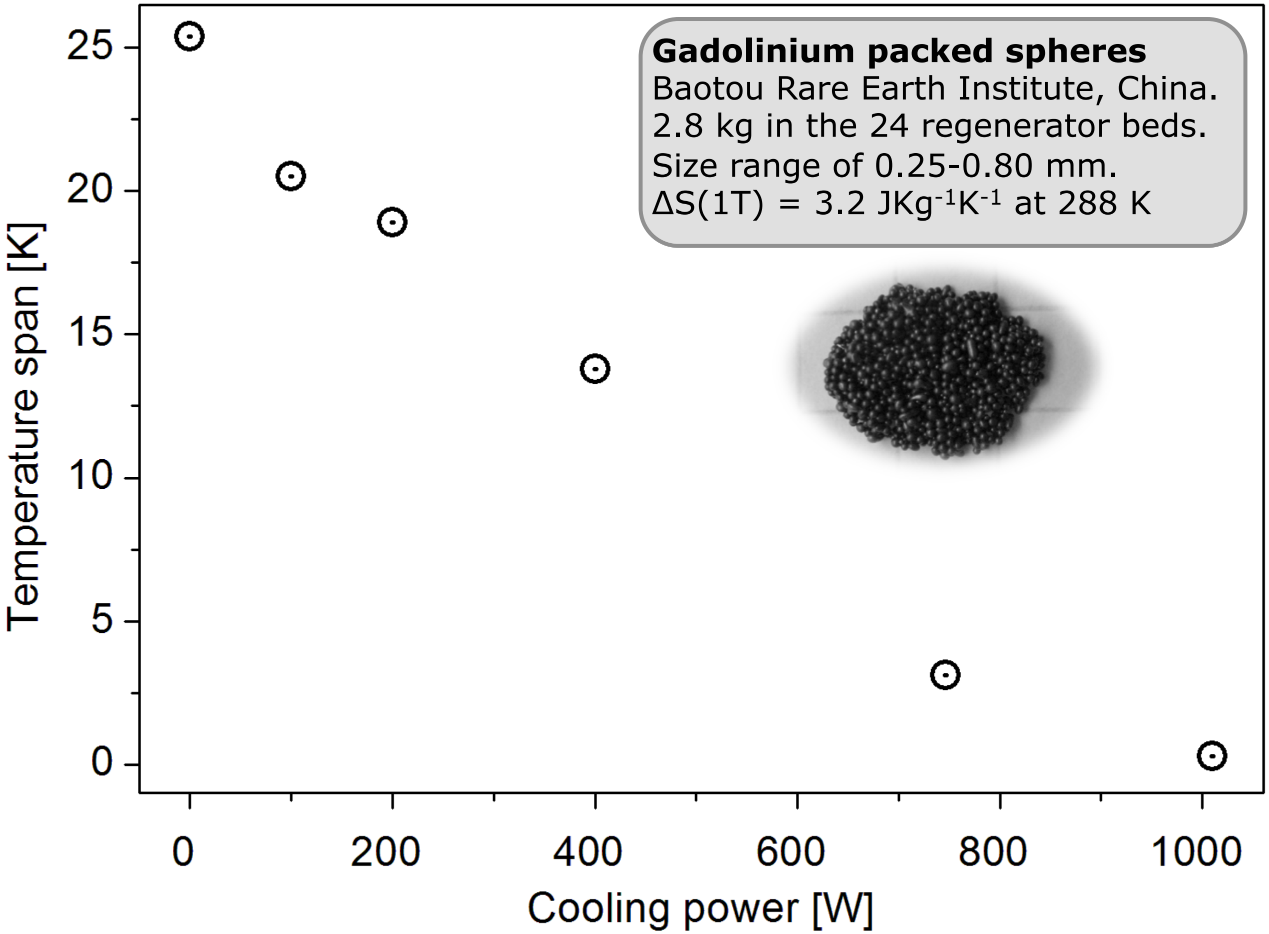


Ingeniøren, April 13 2012

IR- photos at different time



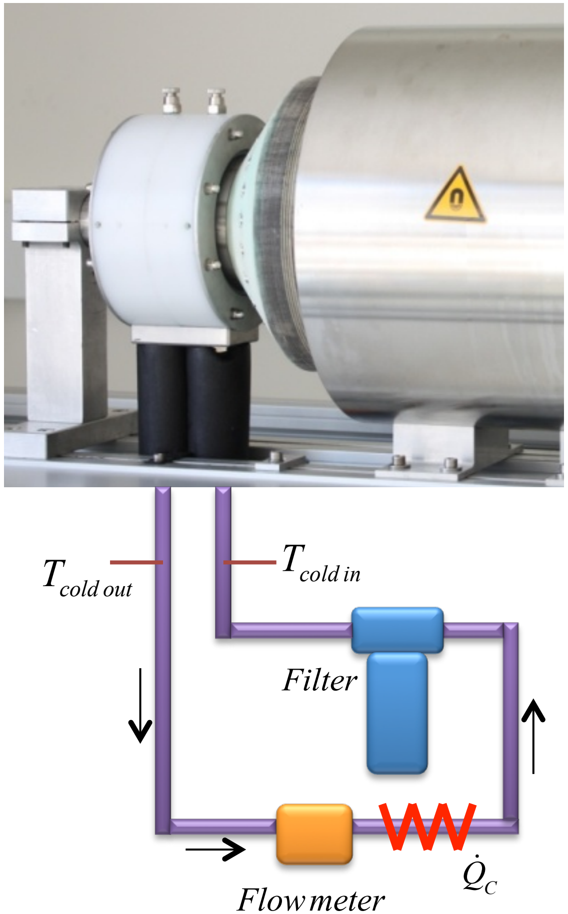
Best performance achieved

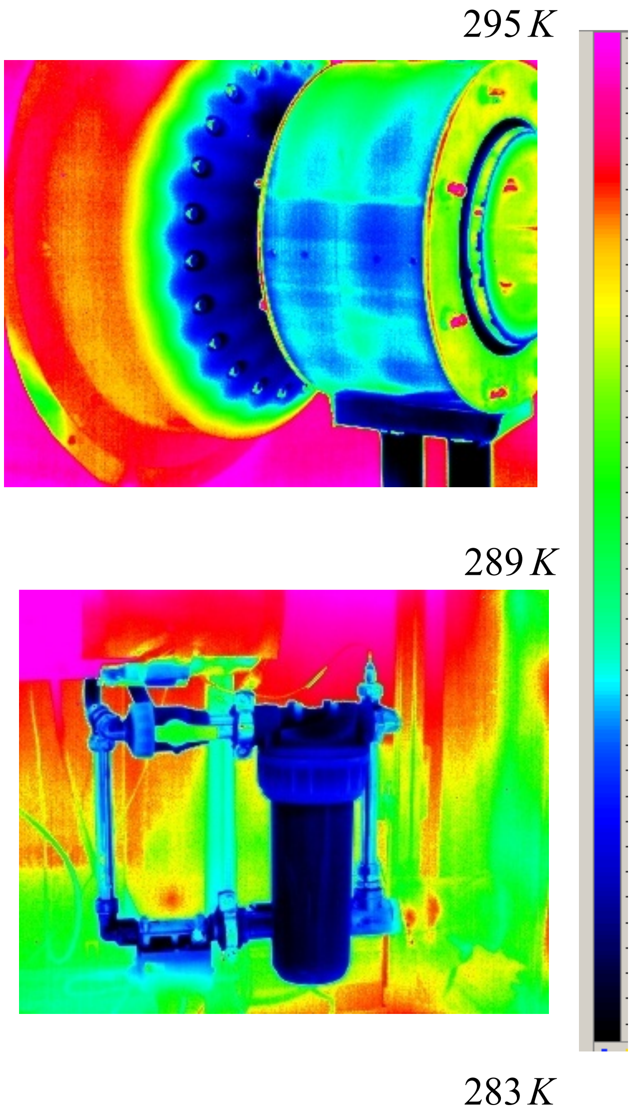


C.R.H. Bahl *et al.* Int. J. Refrigeration (in press 2013)

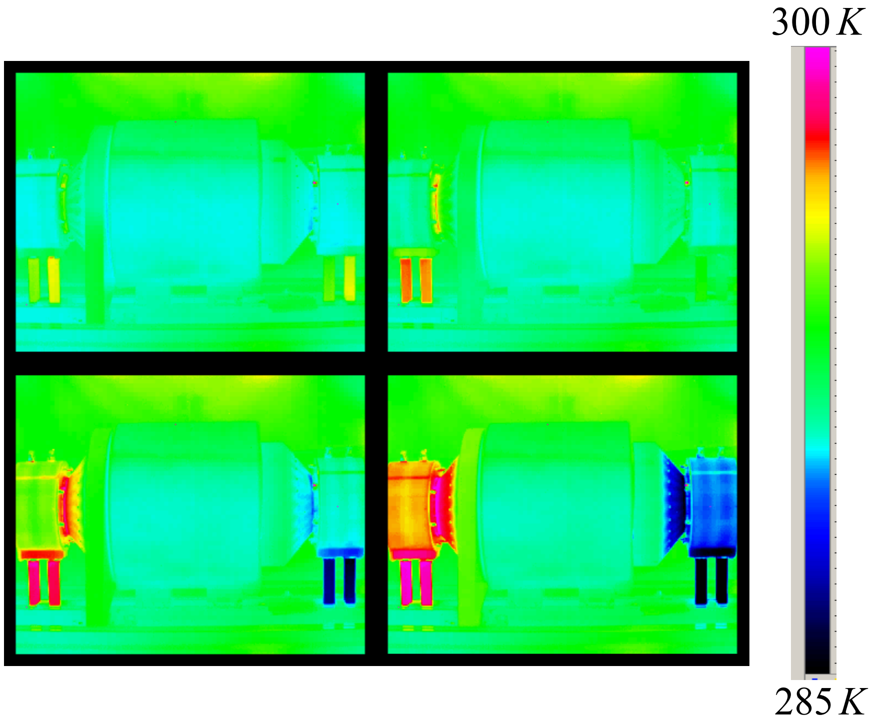
Parasitic losses

Flow distribution friction
Heat transfer from the regenerator housing
Heat losses from the connecting piping
….





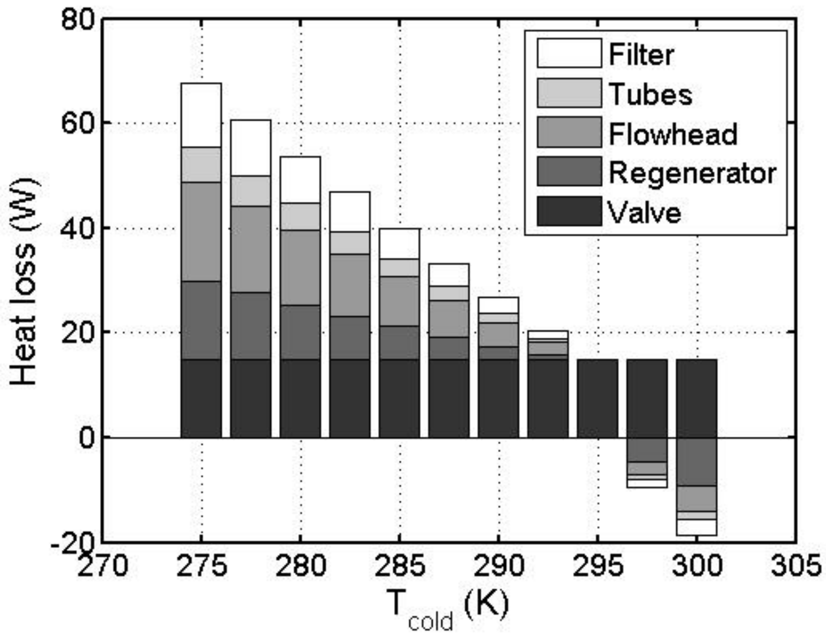
Thermal and frequency-dependent parasitic losses



$$\dot{W}_{\text{valves}} = \dot{W}_{\text{system}} - \dot{W}_{\text{no valves}}$$

$$\dot{Q}_{\text{loss,valve}} \sim 10\, W / Hz$$

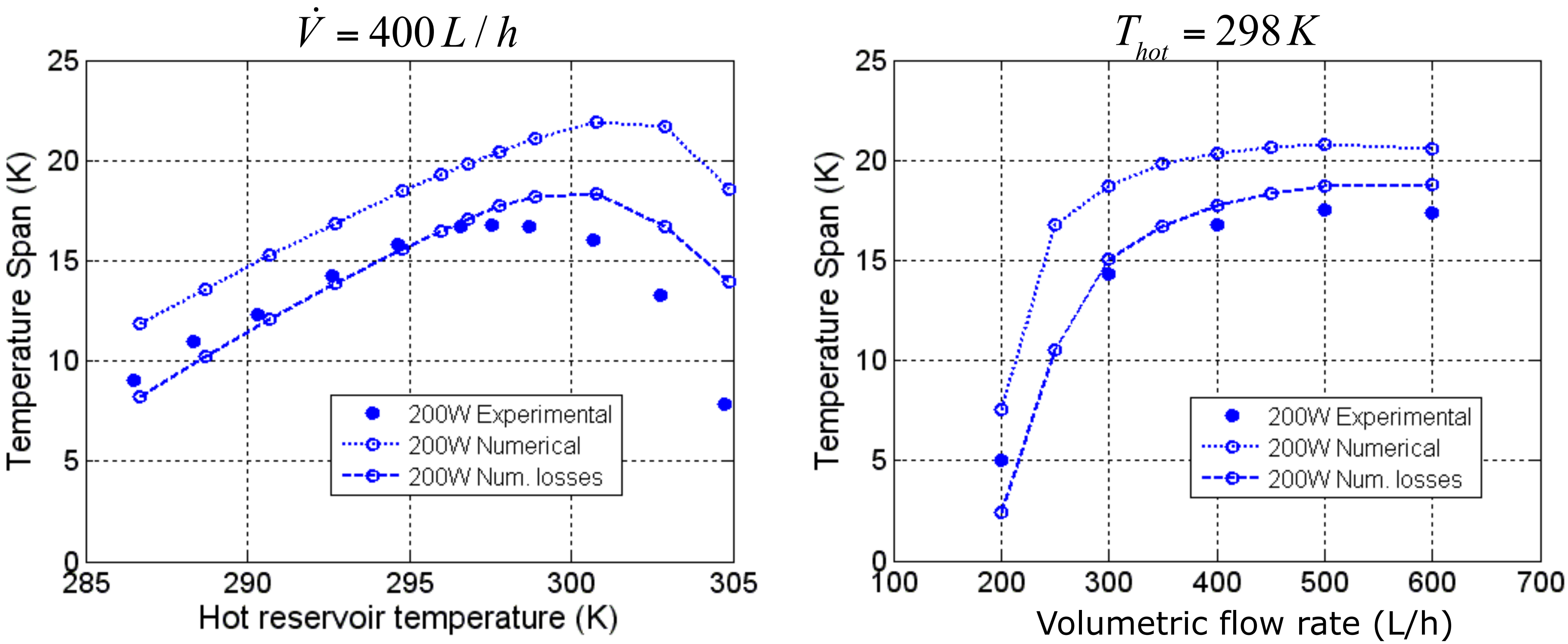
$$T_{ambient} = 295\,K$$
$$T_{hot} = 300\,K$$



$$\dot{Q}_{loss}\left(\Delta T_{span} = 25\,K\right) \sim 74\,W$$

Temperature span as a function of hot reservoir temperature and volumetric flow rate

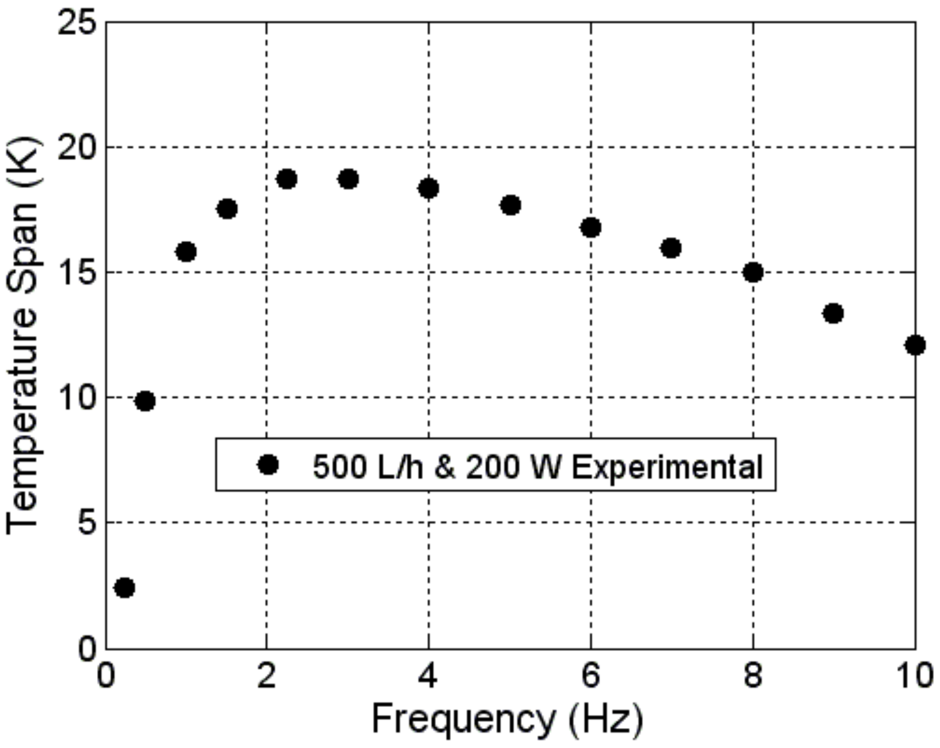
- Frequency = 1.5 Hz
- Cooling power = 200 W



J.A. Lozano, K. Engelbrecht, C.R.H. Bahl, K.K. Nielsen, U.L. Olsen, J.R. Barbosa Jr., A.T. Prata, N. Pryds, *Performance results for a rotary active magnetic regenerator, Applied Energy, 111 (2013)*

Temperature span as a function of frequency

- Cooling capacity = 200 W;
- Hot reservoir temperature = 298 K;
- Peak on temperature span at 2.2 Hz = 19 K ;



Efficiency

- The coefficient of performance (COP) is calculated as:

$$COP = \frac{\dot{Q}_C}{\dot{W}_{pump} + \dot{W}_{motor}}$$

- $\dot{W}_{motor}$ is the total power to the motor, gear box, pulley etc.

- $\dot{W}_{pump} = \dfrac{\dot{V}\Delta P}{\eta_{pump}}$ is the pumping power ($\eta_{pump}=0.7$)

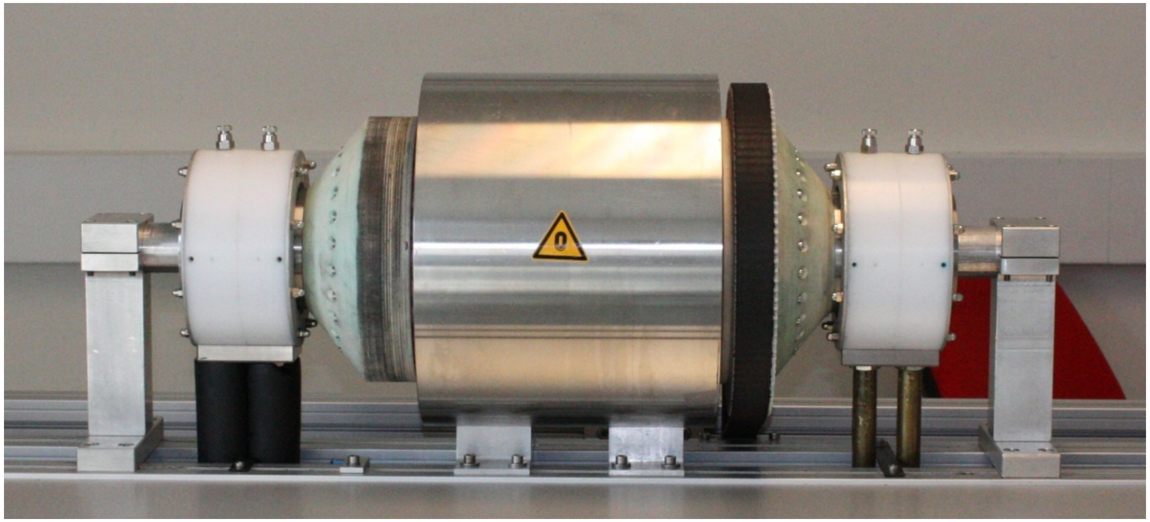
- **COP = 1.8** at 400 W cooling, 8.9 K temp. span. (2.8 with no friction)
- **COP = 0.8** at 200 W cooling, 15.4 K temp. span. (1.4 with no friction)

K. Engelbrecht *et al.* Int. J. Refrigeration. **35** (2012) 1498
J.A. Lozano *et al.* Applied Energy 111 (2013) 669–680

Best results to date with Gd spheres, 0.5mm

- Maximum load of **1010 W at zero temperature span**
- Temperature span of **25.4 K at no-load**
- Maximum frequency **10 Hz**

- Temperature span of **20.5 K at 100 W**
- Temperature span of **18.9 K at 200 W**
- Temperature span of **13.8 K at 400 W**

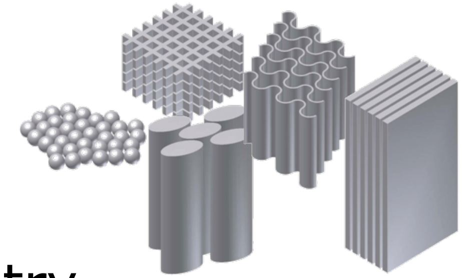


K. Engelbrecht, D. Eriksen, C.R.H. Bahl, R. Björk, J. Geyti, J.A. Lozano, K.K. Nielsen, F. Saxild, A. Smith, N. Pryds : Experimental results for a noval rotary active magnetic regenerator. Vol.35(2012)1498-1505

'Best Paper of the Year'
published in the IJR in 2012/2013

Where do we go from here?

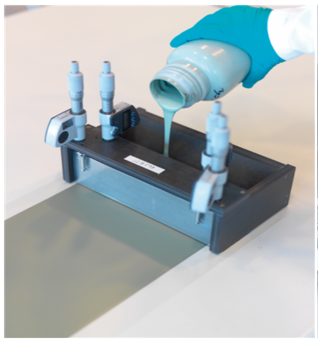
- Several devices have now proven the technology.
- Temperature span and cooling power are now close to commercial requirements.
- Needed:
  - Higher efficiency
  - Reduction in size
  - Improved regenerator geometry
  - Testing more materials in actual devices, especially 1st order materials.



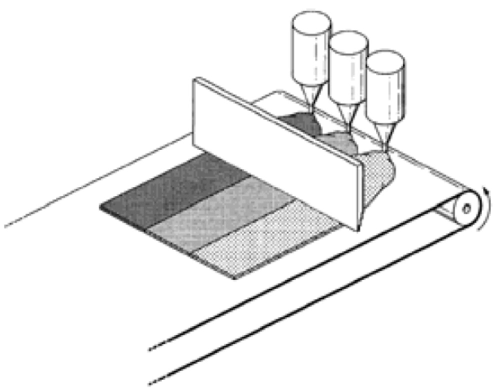
Some industrial scale shaping methods

Tape casting

- Slurries are cast into thin sheets and sintered into plates




- Option of grading materials



Extrusion

- A viscous paste is pressed through a die and sintered into a monolith.

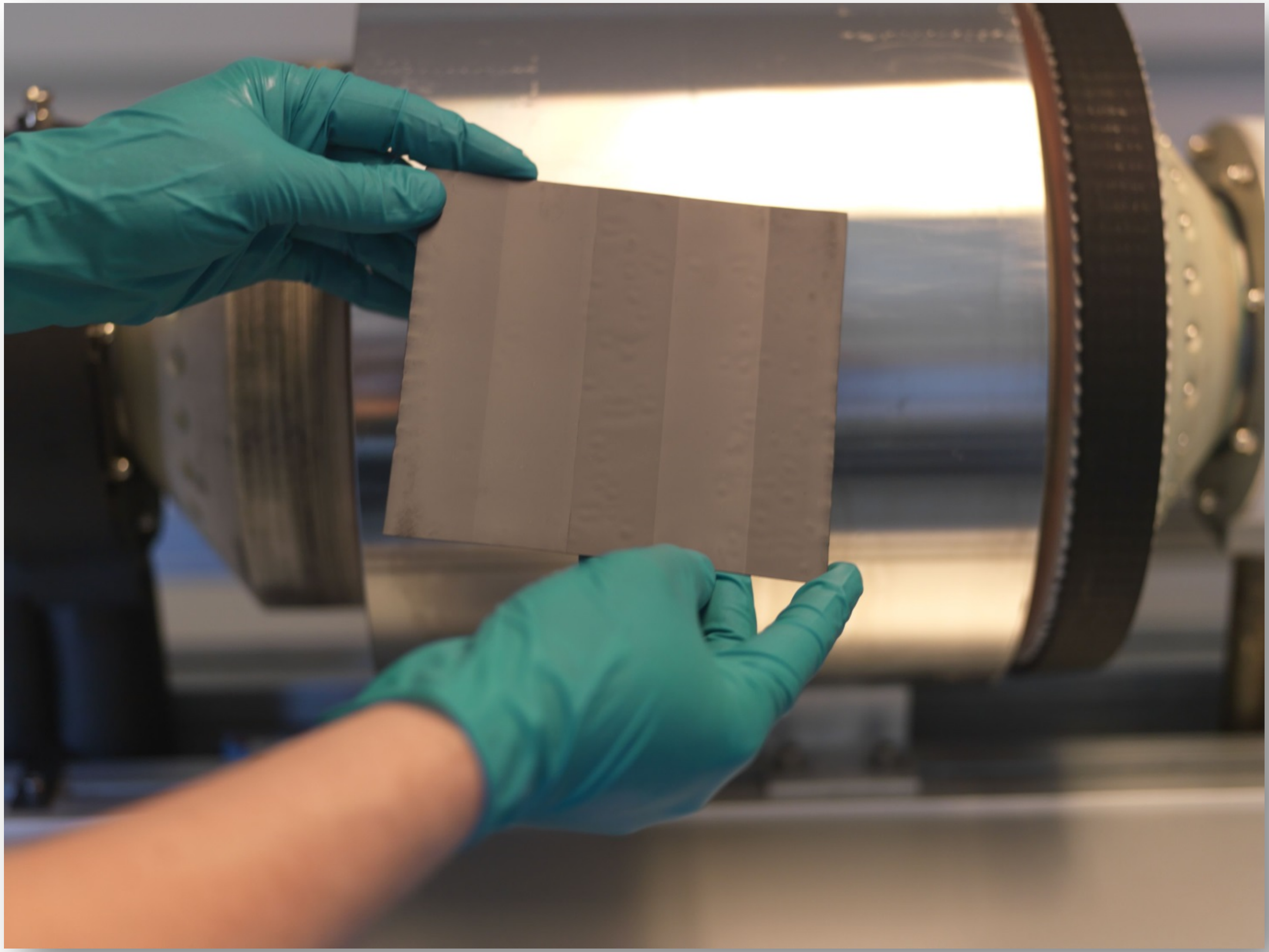

- Regenerator parts can be made in one process.

Materials Views
www.MaterialsViews.com
ADVANCED ENERGY MATERIALS
www.advenergymat.de
REVIEW

Materials Challenges for High Performance Magnetocaloric Refrigeration Devices

Anders Smith, Christian R.H. Bahl, Rasmus Bjørk, Kurt Engelbrecht, Kaspar K. Nielsen, and Nini Pryds*

Available online, DOI: 10.1002/aenm.201200167



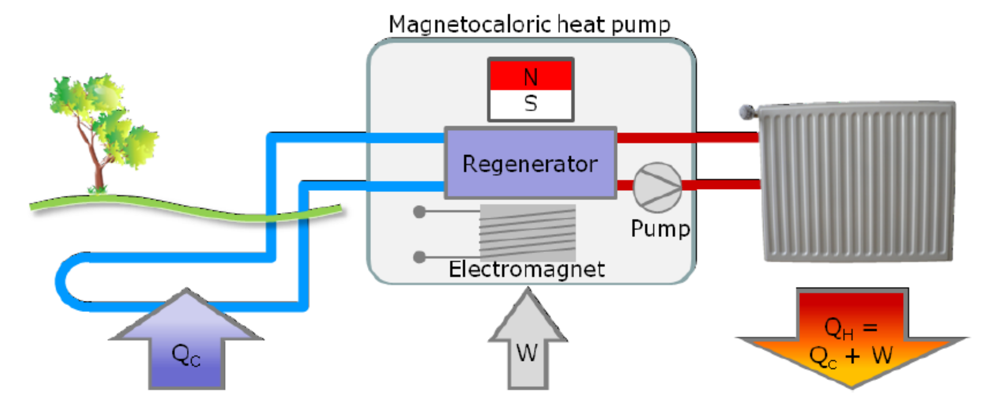
ENOVHEAT

DTU

Efficient Novel Magnetocaloric Heat Pumps

The main objective of the project is to build the necessary scientific and technological foundation for the realisation of high-efficiency heat pumps based on magnetocaloric technology, focused on a system for the residential sector.

Idea



Project period: 2013-2017

Funding: 2.5 M€ from Danish Council for Strategic Research, Programme Commission on Sustainable Energy and Environment.

Partners

DTU Technical University of Denmark

University of Southern Denmark

Aalborg University

Imperial College London

University *of Ljubljana*
Faculty of Mechanical Engineering

TECHNOFLEX POWER TO PERFORM

alpcon

VAC VACUUMSCHMELZE

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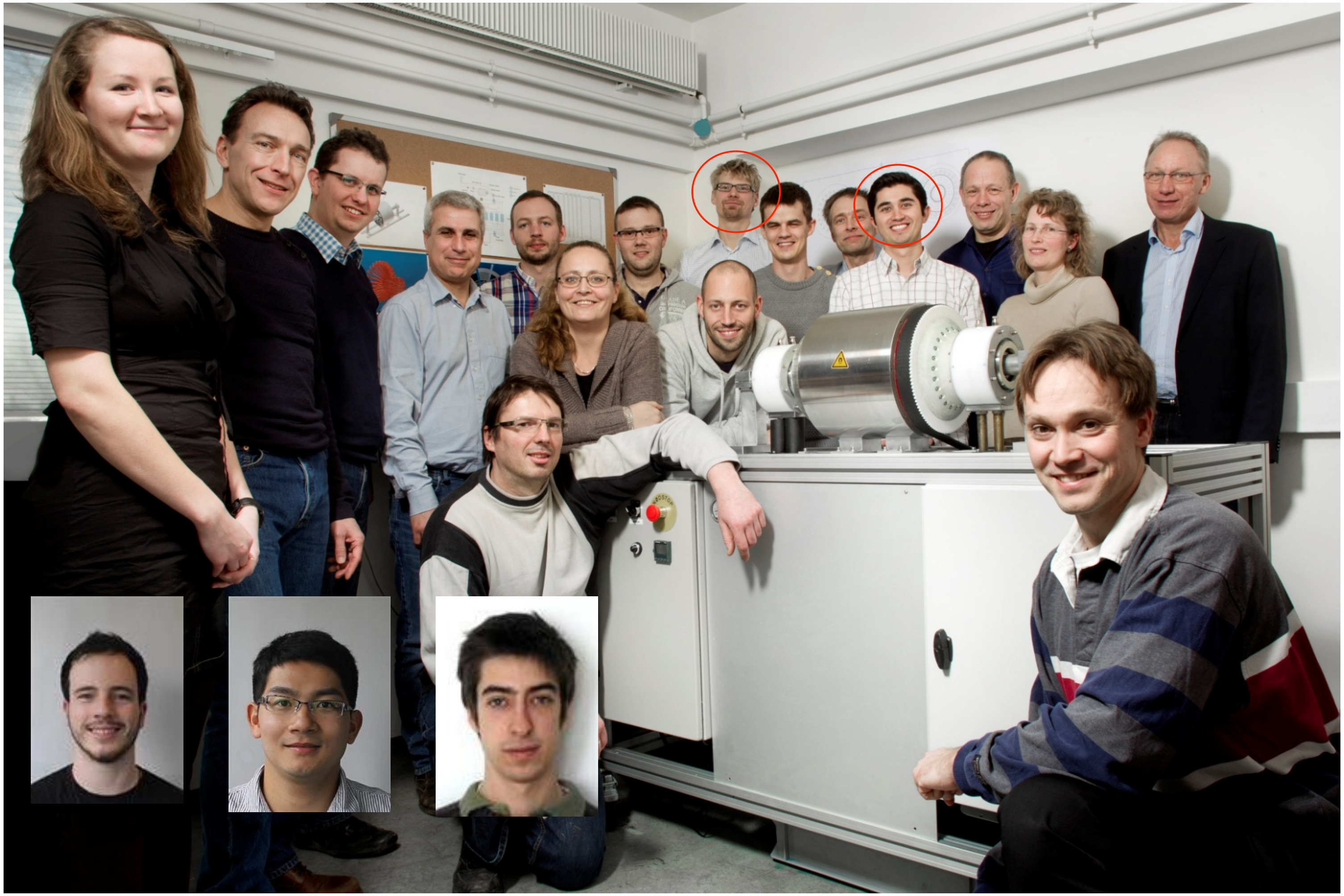
Conclusions

- Care must be taken when determining COP for research devices such as the one at DTU
- Loss mechanisms in order of importance are valve friction, thermal losses, uneven drive torque, valve leakage
  - Valve friction was shown to account for ~30% of the motor power
- Parasitic heat losses can significantly reduce the effective cooling power and subsequently COP
  - Good insulation of the cold end is necessary to reach high COP

The magnetic refrigeration work group



Thank you for your attention.