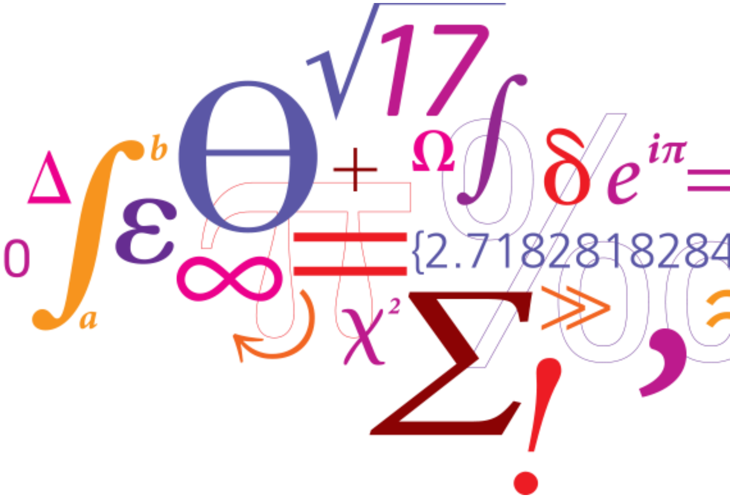
Improved efficiency of a rotary active magnetic regenerator

Magnetocaloric cooling (and heating) group DTU



DTU Energy

Department of Energy Conversion and Storage

Organization

Theoretical background

- MCM property effects on AMR performance
- Regenerator effects on AMR performance

Experimental efforts at DTU

- Device background and description
- Device improvements
- Experimental results

Other work at DTU

- Heat transfer optimization
- ENOVHEAT project

Studying the Effect of Regenerator Effectiveness on AMR

- Start with a fixed regenerator shape – 13x18 mm, 100 mm long (large prototype) and operating conditions

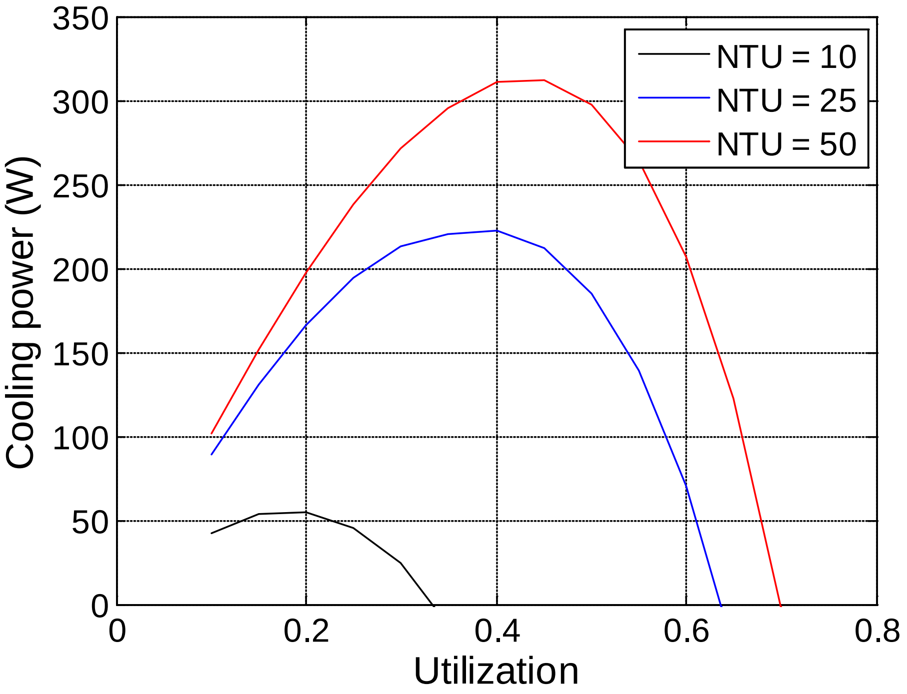
- Temperature span is 25 K

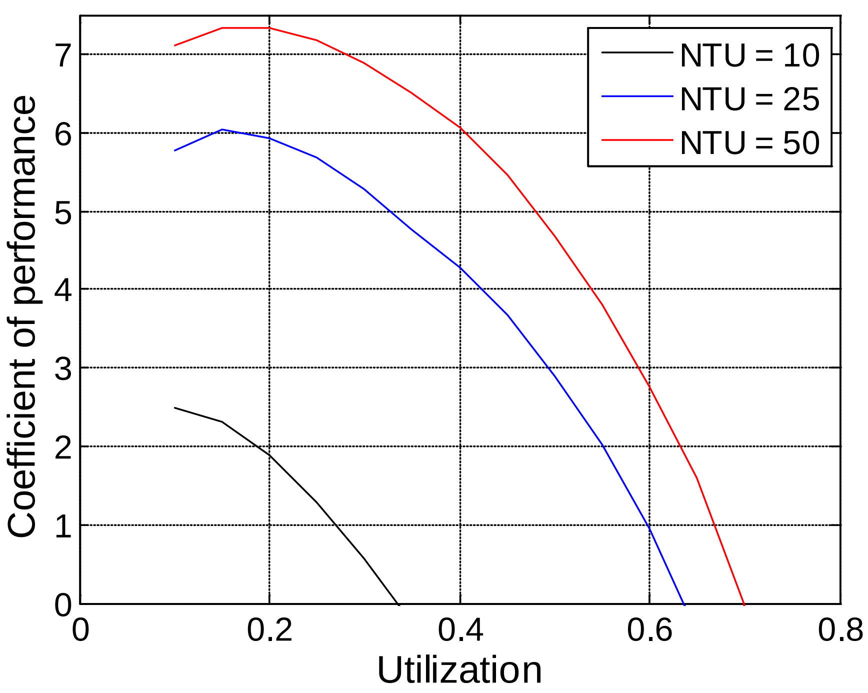
$$U = \frac{c_f \, \dot{m} \, \tau}{C_f + C_s}$$

- Set a range of utilizations

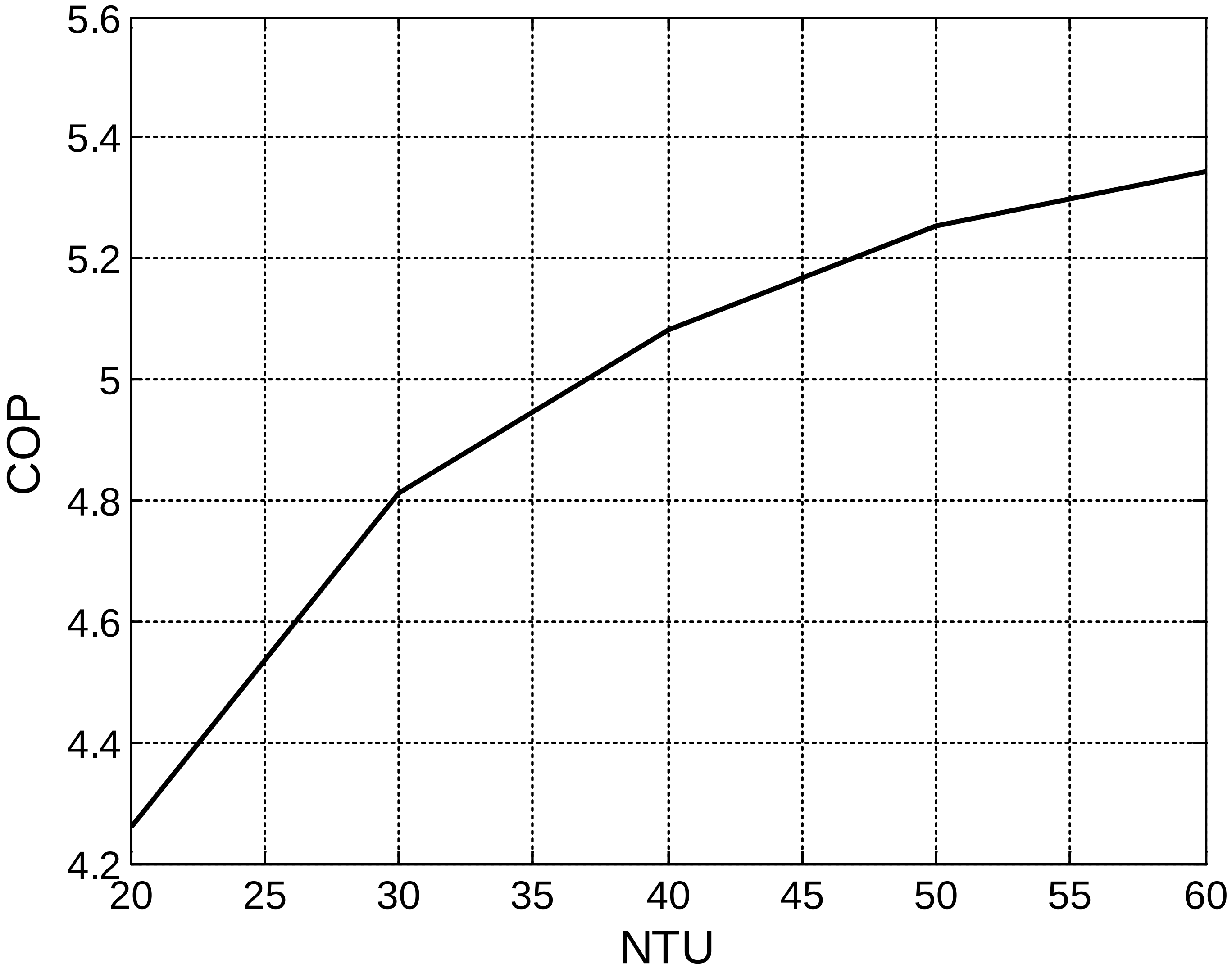
- Scale the heat transfer in order to hold NTU constant

Active Regenerator Performance vs *NTU* - 25K span





Active Regenerator Efficiency, Fixed Cooling Power, 25 K span



Packed Sphere Regenerator Performance

- High heat transfer performance
  - Small particle sizes available

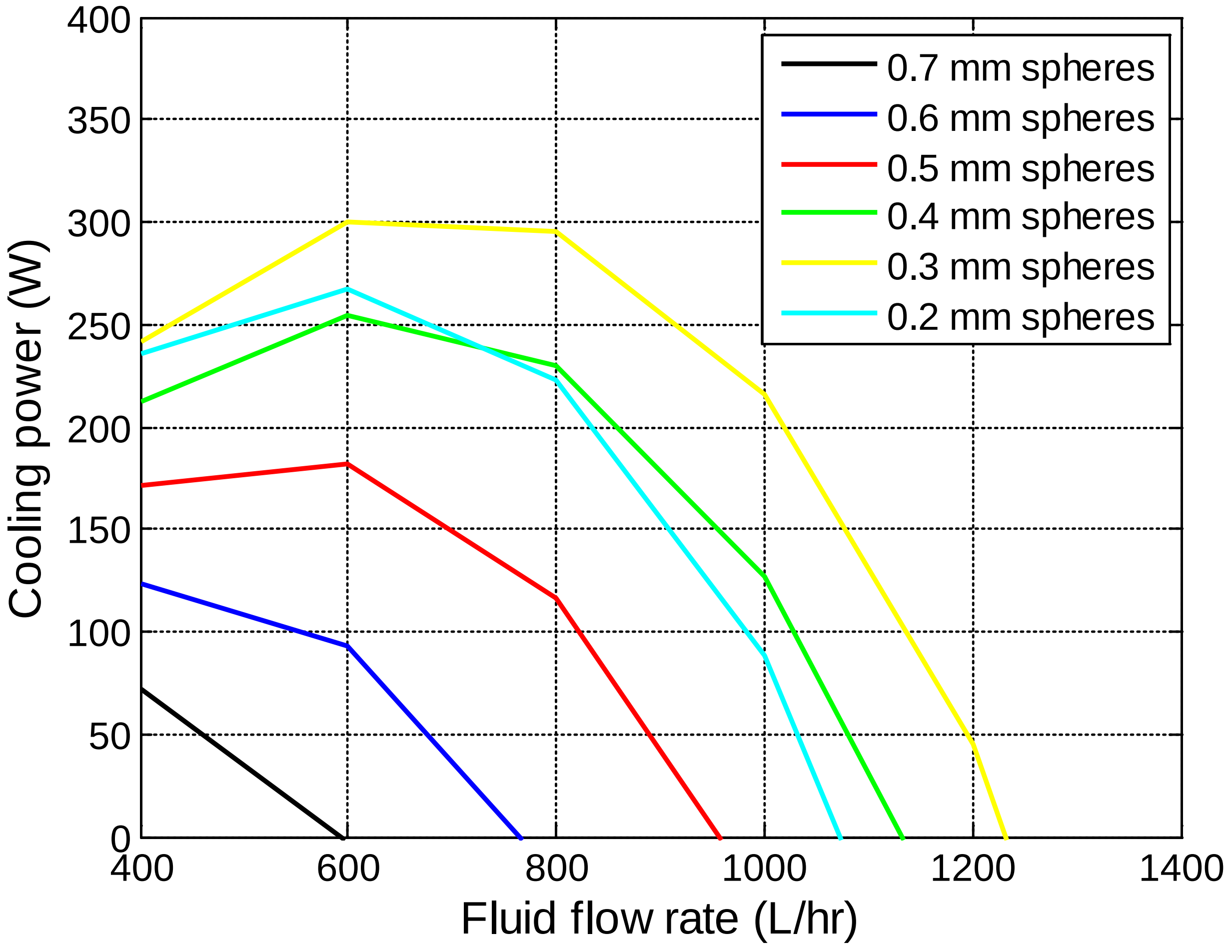
- Relatively easy construction, including layered regenerators

- High pressure drop

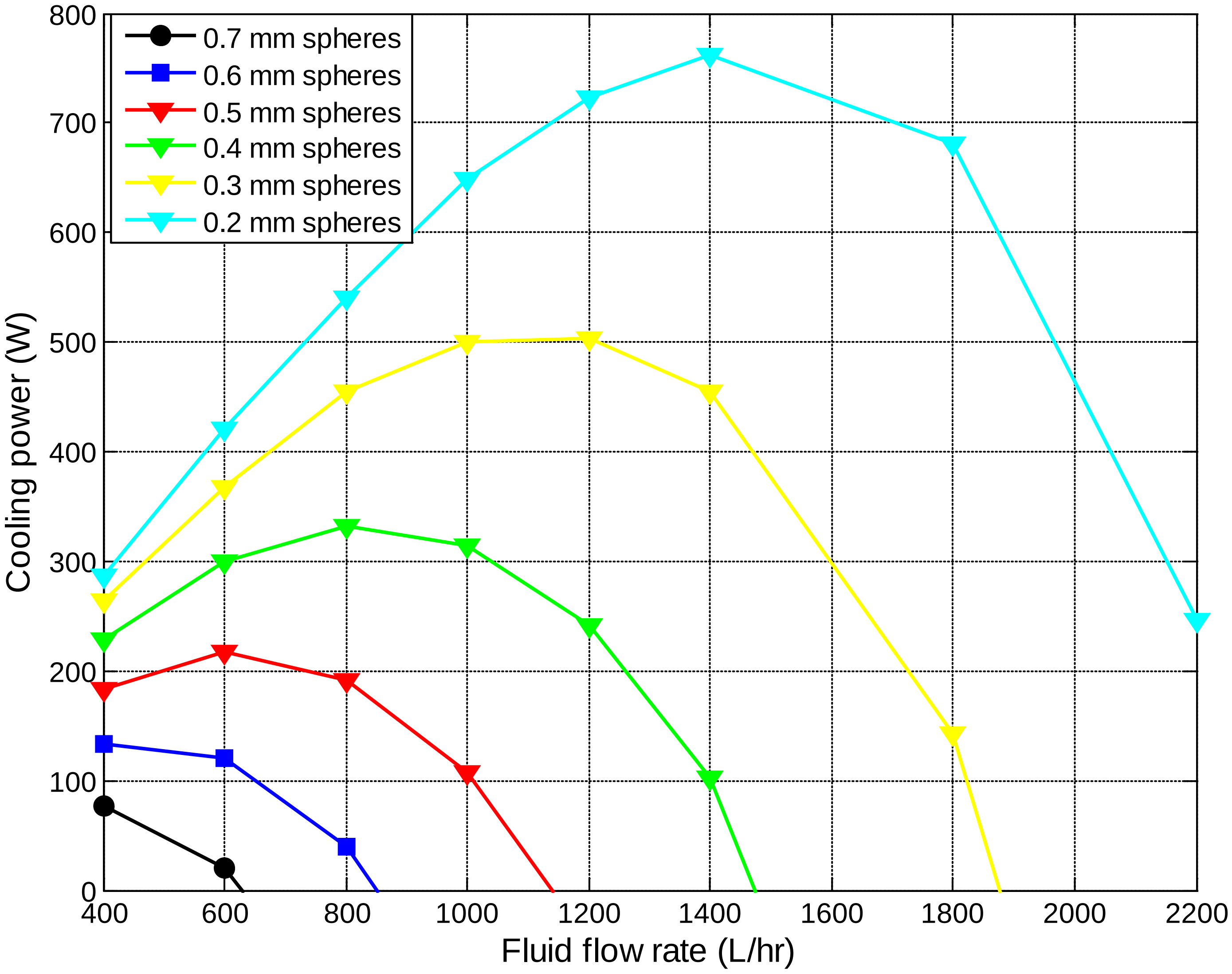
$$COP = \frac{\dot{Q}_c}{\dot{W}_{pump} + \dot{W}_{motor}}$$

Packed Sphere AMR Performance

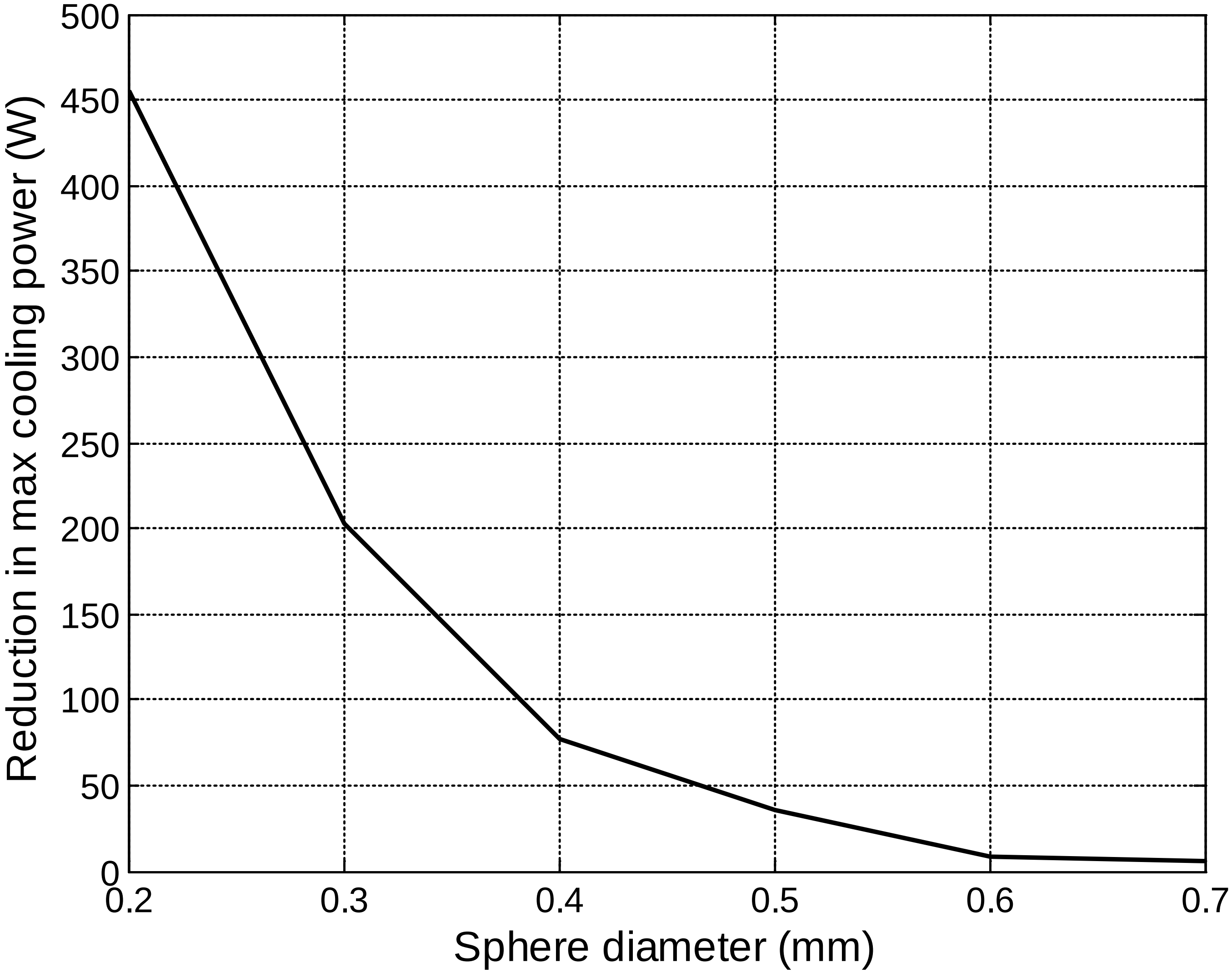
f=2 Hz, ΔT=24 K



Packed Sphere, no pressure drop



Reduction in cooling power due to viscous dissipation



Packed Sphere Discussion

- Pressure drop is a huge problem
  - Cooling power reduction
  - COP reduction due to increased pump power
  - Requires higher regenerator housing strength

- Pressure drop can be reduced by increasing cross-sectional area but this usually makes life difficult for magnet designers

- Room temperature AMRs with packed sphere regenerators will probably never be commercially relevant for widespread applications

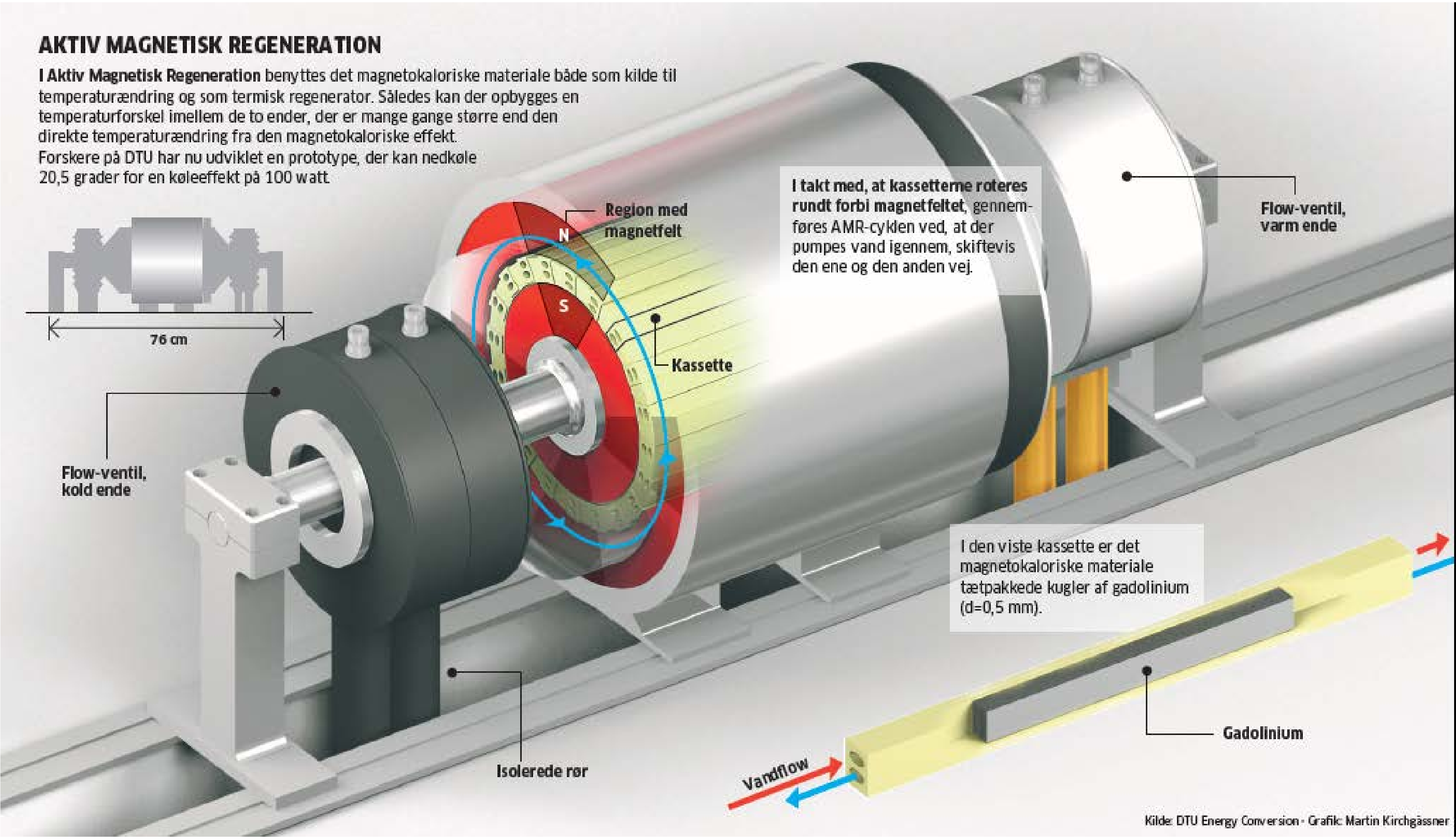
Parallel Plate Regenerators

- Exhibit attractive pressure drop to heat transfer characteristics

- Relatively low disruption of the fluid flow and low specific surface area mean that small dimensions are required for high *NTU*
  - Roughly 50 μm plate thickness and 50 μm spacing

- Constructing high performance plate regenerators is difficult

1st rotary AMR prototype



AKTIV MAGNETISK REGENERATION

I Aktiv Magnetisk Regeneration benyttes det magnetokaloriske materiale både som kilde til temperaturændring og som termisk regenerator. Således kan der opbygges en temperaturforskel imellem de to ender, der er mange gange større end den direkte temperaturændring fra den magnetokaloriske effekt.
Forskere på DTU har nu udviklet en prototype, der kan nedkøle 20,5 grader for en køleeffekt på 100 watt.

I takt med, at kassetterne roteres rundt forbi magnetfeltet, gennemføres AMR-cyklen ved, at der pumpes vand igennem, skiftevis den ene og den anden vej.

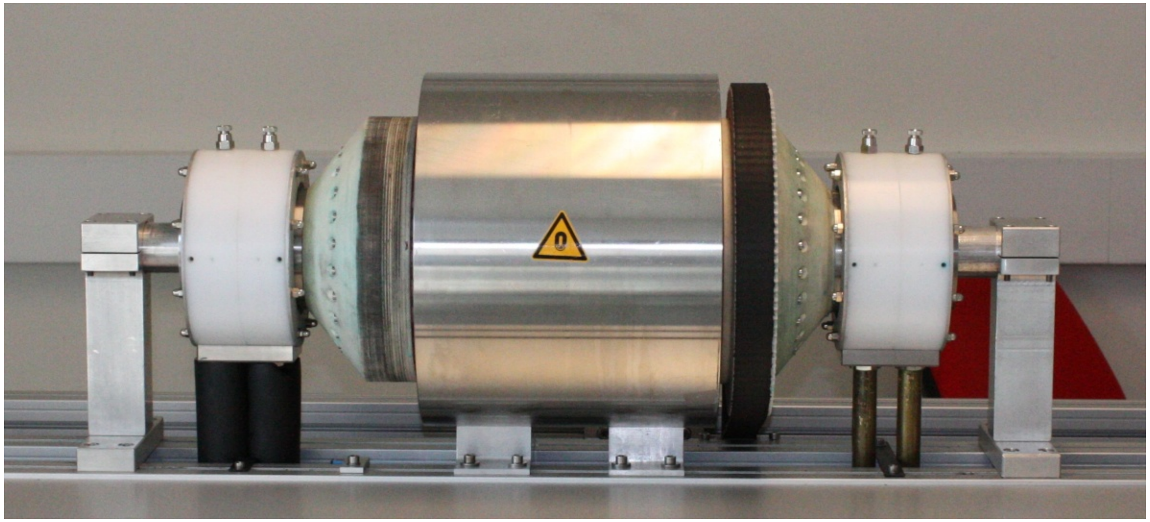
I den viste kassette er det magnetokaloriske materiale tætpakkede kugler af gadolinium (d=0,5 mm).

Kilde: DTU Energy Conversion - Grafik: Martin Kirchgässner

First large active magnetic regenerator (AMR) at DTU

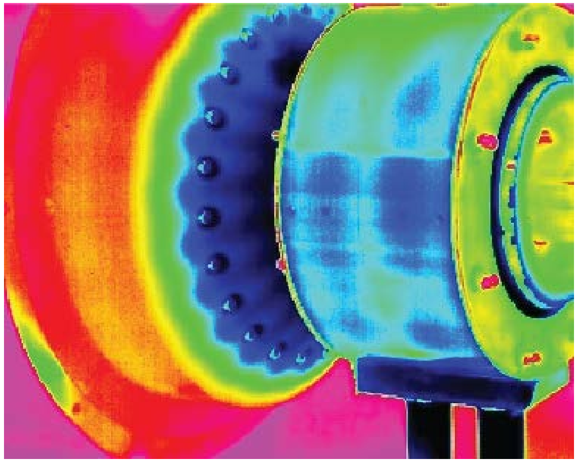
- Maximum load of **1010 W at zero temperature span**
- Temperature span of **25.4 K at no-load**
- Maximum frequency **10 Hz**

- 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**



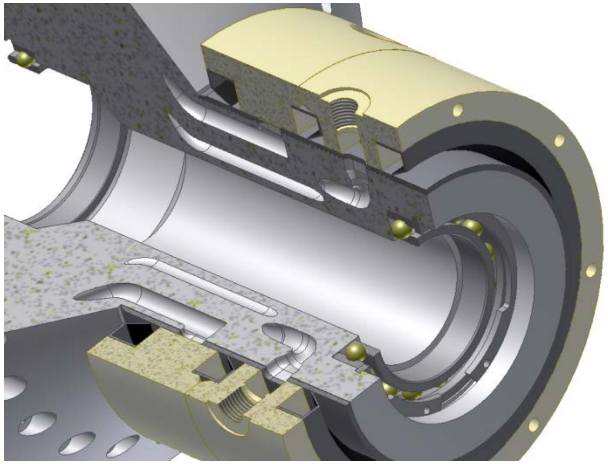
K. Engelbrecht et al., 2012, *Int. J. Ref.*, 35(6): 1498-1505.

Main challenges from previous AMR



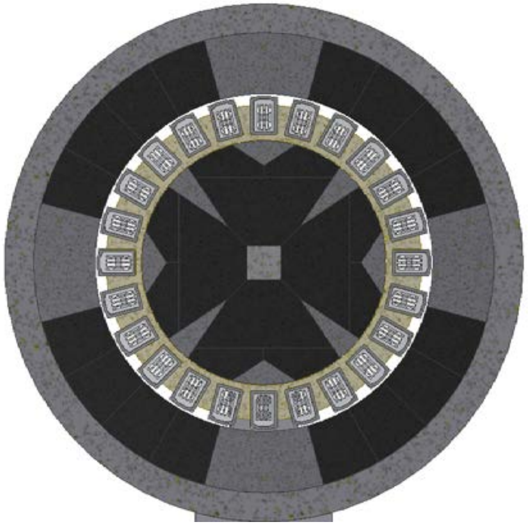
Heat leakage

- Decreases cooling power



Valve and seal friction

- Increased motor work
- Heat dissipation subtracts from cooling power



Only 37 % MCM in magnet gap (cross section)

- Expensive magnet wasted
- Uneven torque

Design focus points

Magnet:

- 2D AMR model optimization combined with FE magnet optimization
- Mechanically simple and efficient rotation relative to regenerator

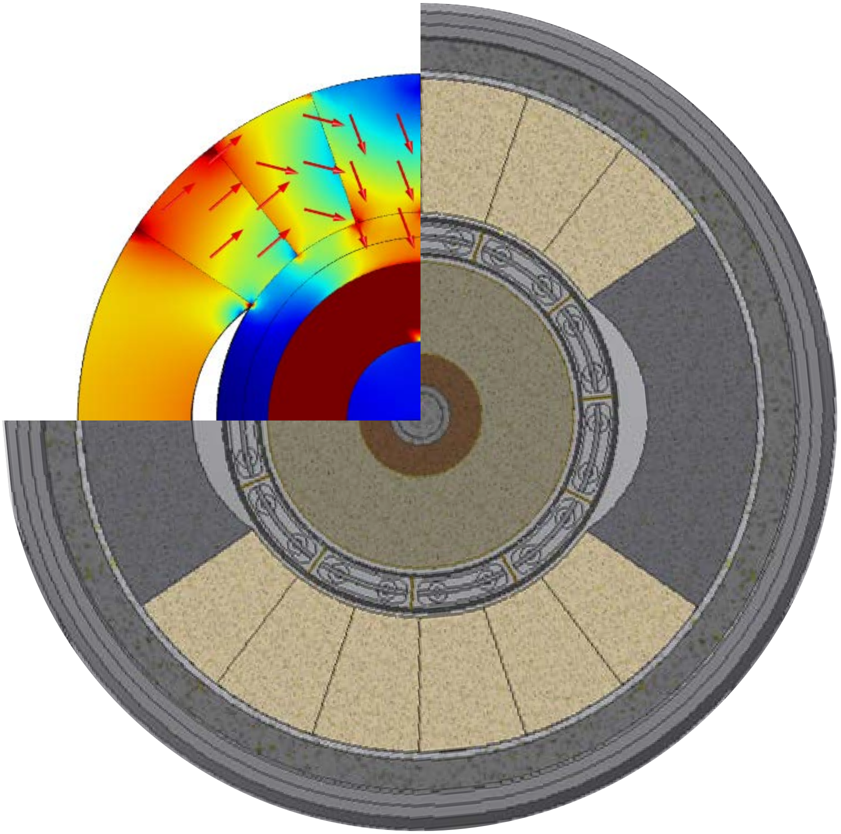
Regenerator:

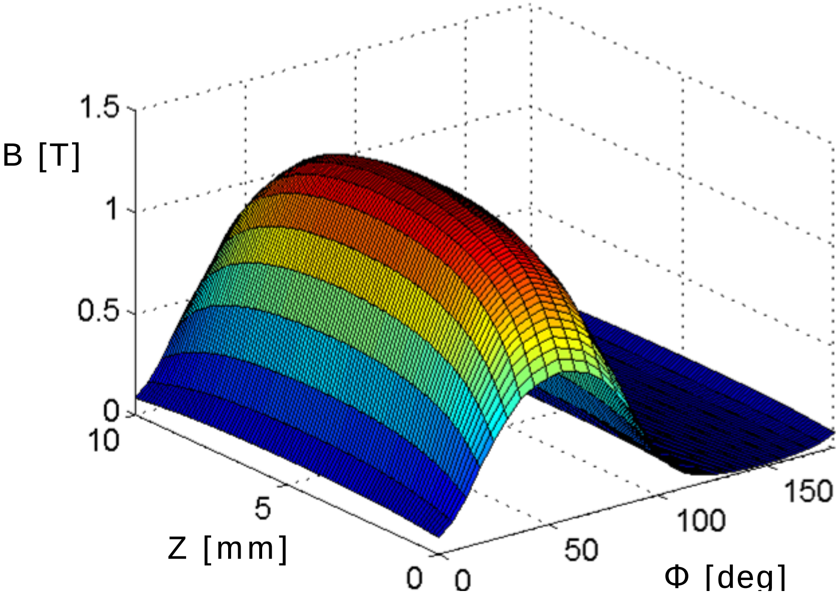
- 2D AMR model optimization of bed dimensions for magnetic field
- Utilize magnetized volume: Minimize regenerator housing
- Minimize uneven torque: Minimize bed spacing
- Minimize regenerator heat leakage: insulating air gap

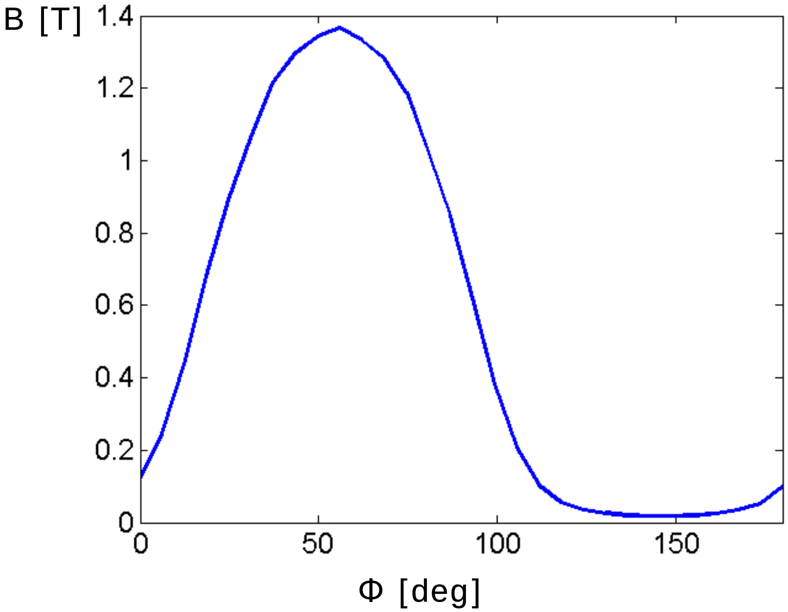
Flow system:

- Control flow profile in beds based on 2D AMR model optimizations
- Minimize friction
- Eliminate internal leak paths

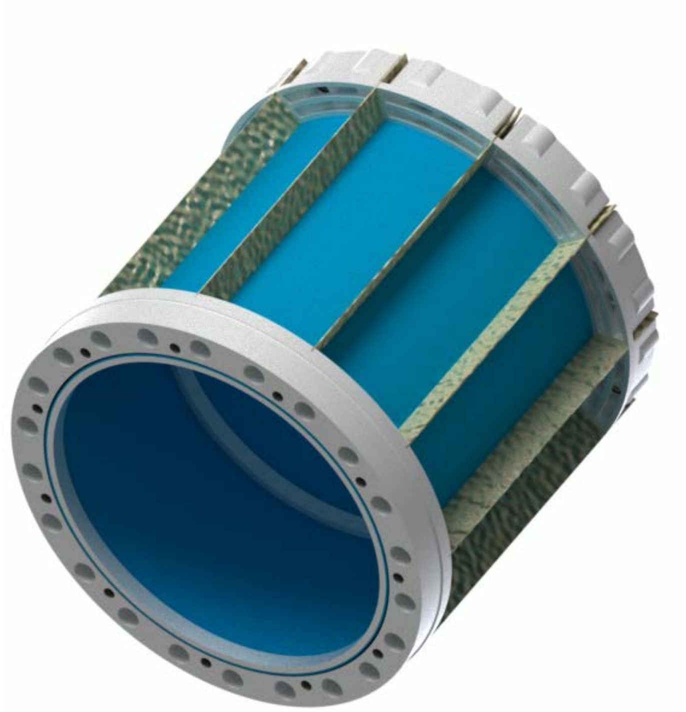
Magnet design



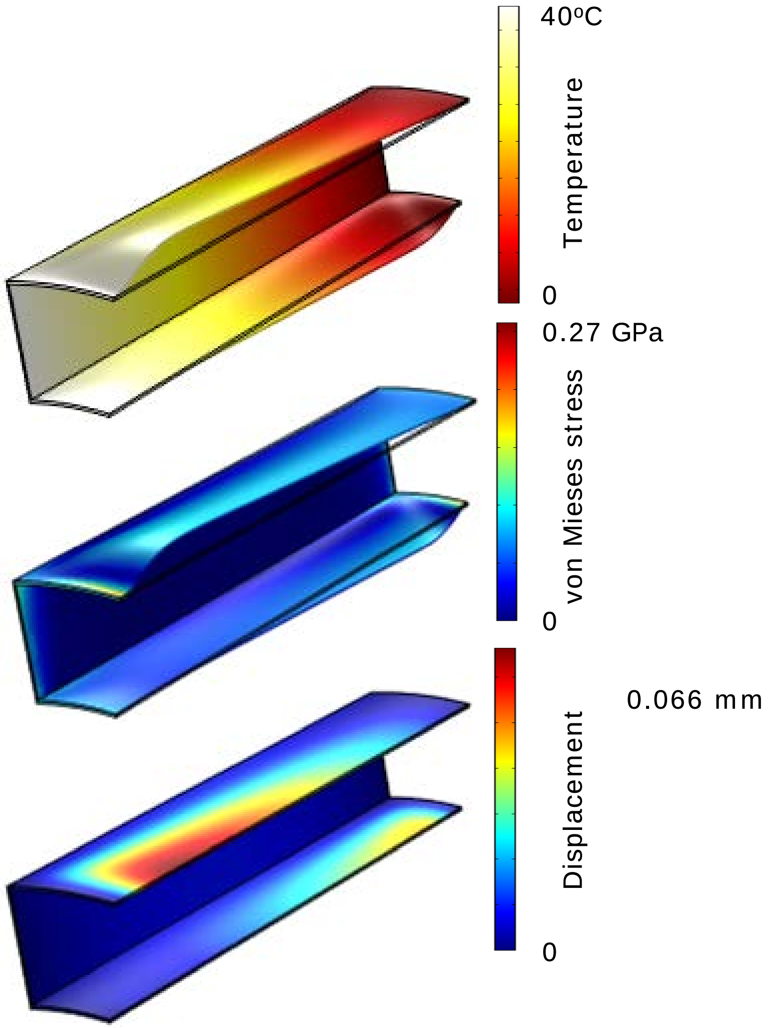




Regenerator design

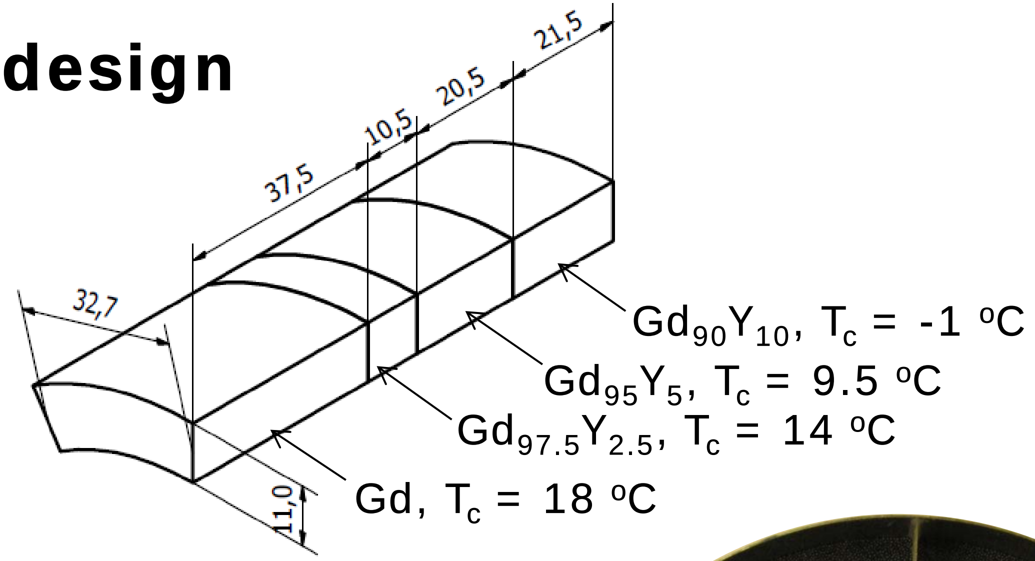


- 11 compartments
- Separation walls: 0.5 mm Glass fiber
- Housing: 0.5 mm stainless steel cylinders



Structural simulations at ΔT = 40 K and P = 10 bar

Regenerator design



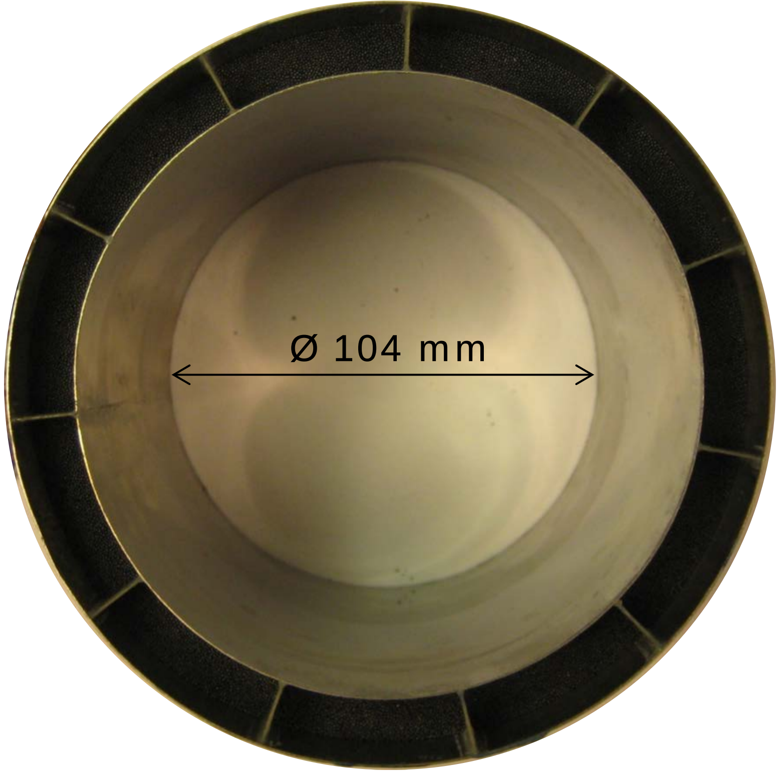
$Gd_{90}Y_{10}$, T_c = -1 °C

$Gd_{95}Y_5$, T_c = 9.5 °C

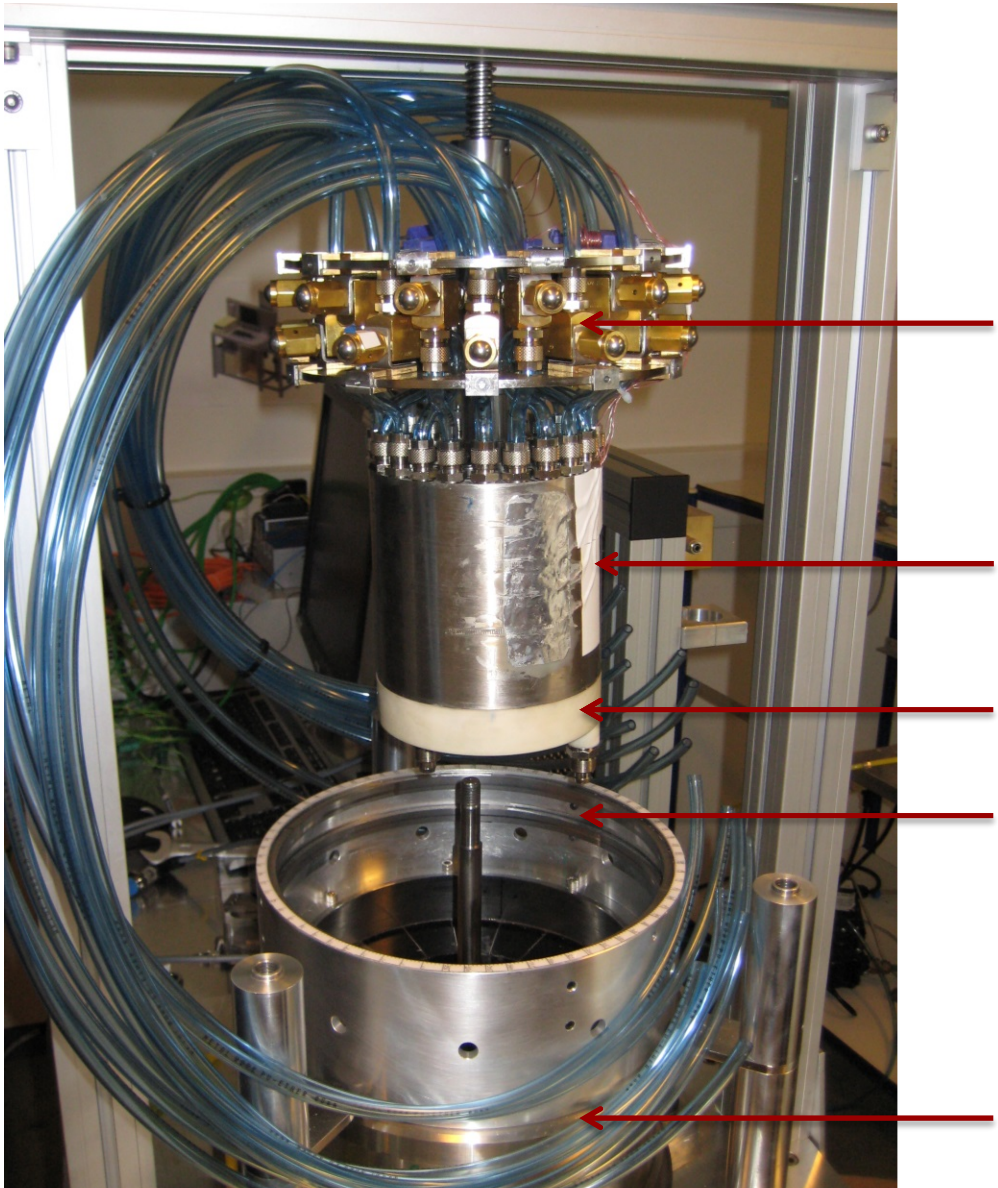
$Gd_{97.5}Y_{2.5}$, T_c = 14 °C

Gd, T_c = 18 °C

- Gd/GdY spheres from SANTOKU for enhanced ΔT
- 1.7 kg MCM
- Sphere diameter: 0.3 mm - 0.6 mm
- Housing takes up 9.7 % of regenerator cross section



Regenerator with flow system assembly



Poppet valve system

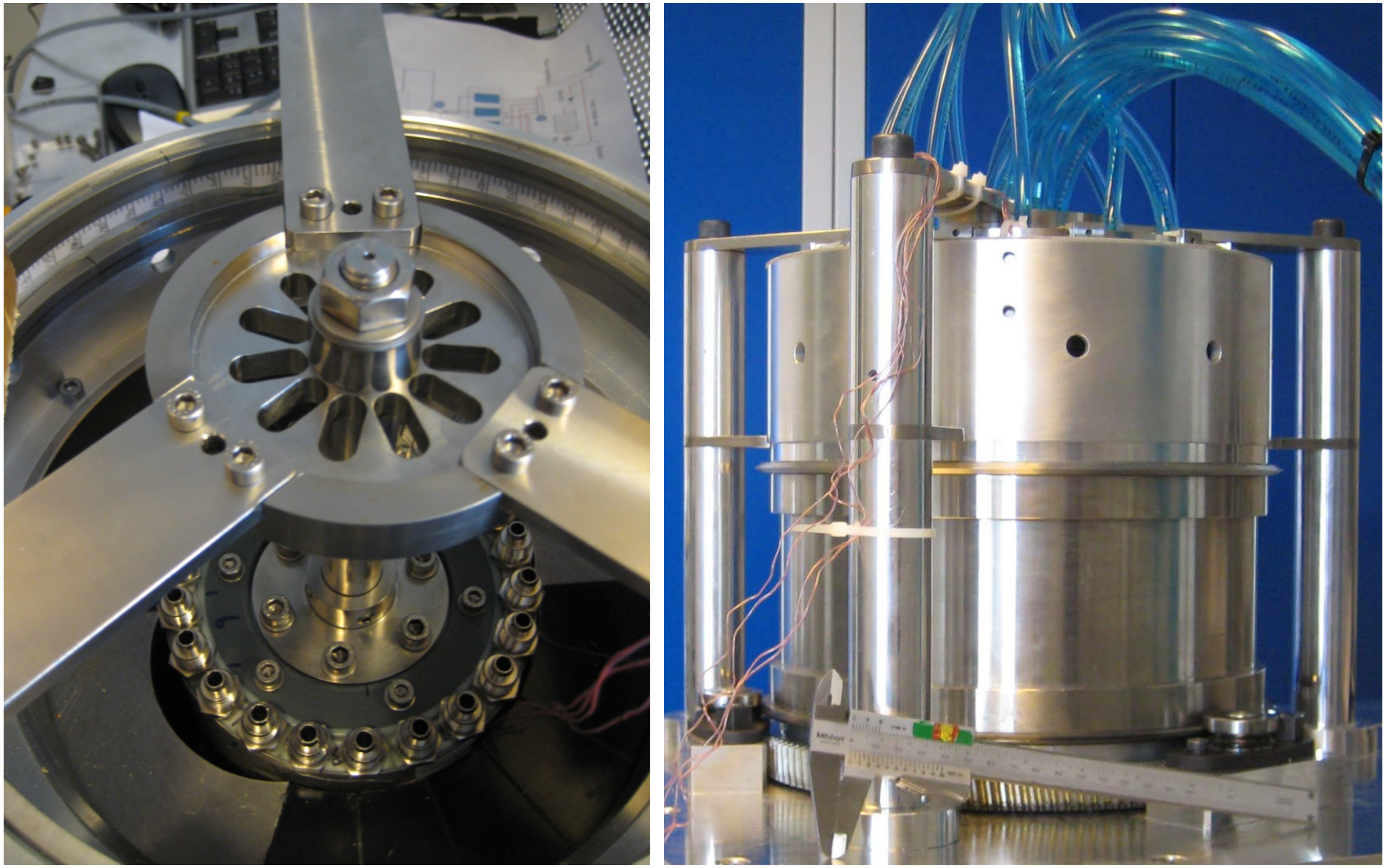
Active magnetic regenerator

Cold side check valve system

Cam rings

Rotating magnet

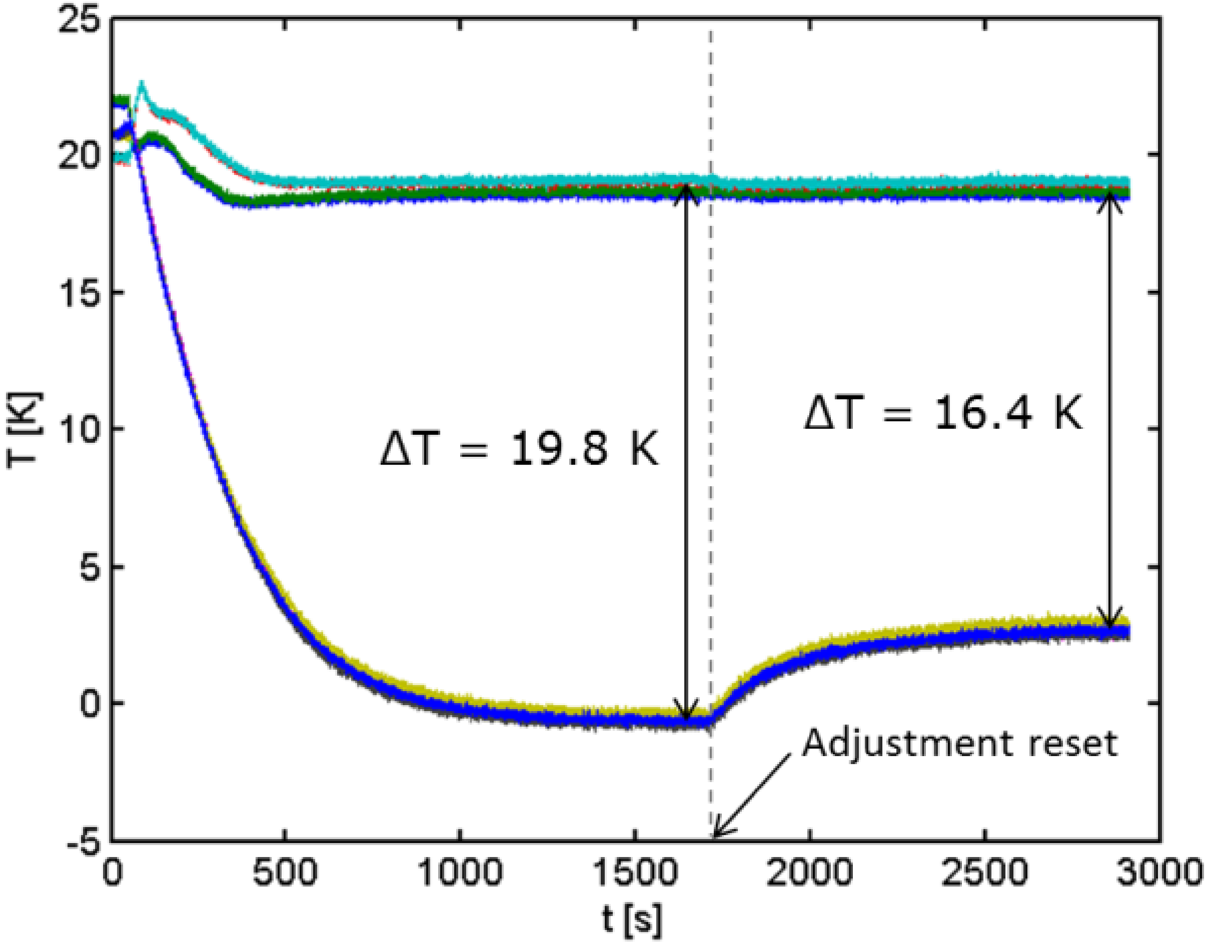
Final construction…



D. Eriksen et al., 2015, *Int. J. Refrigeration* available online

The machine in action

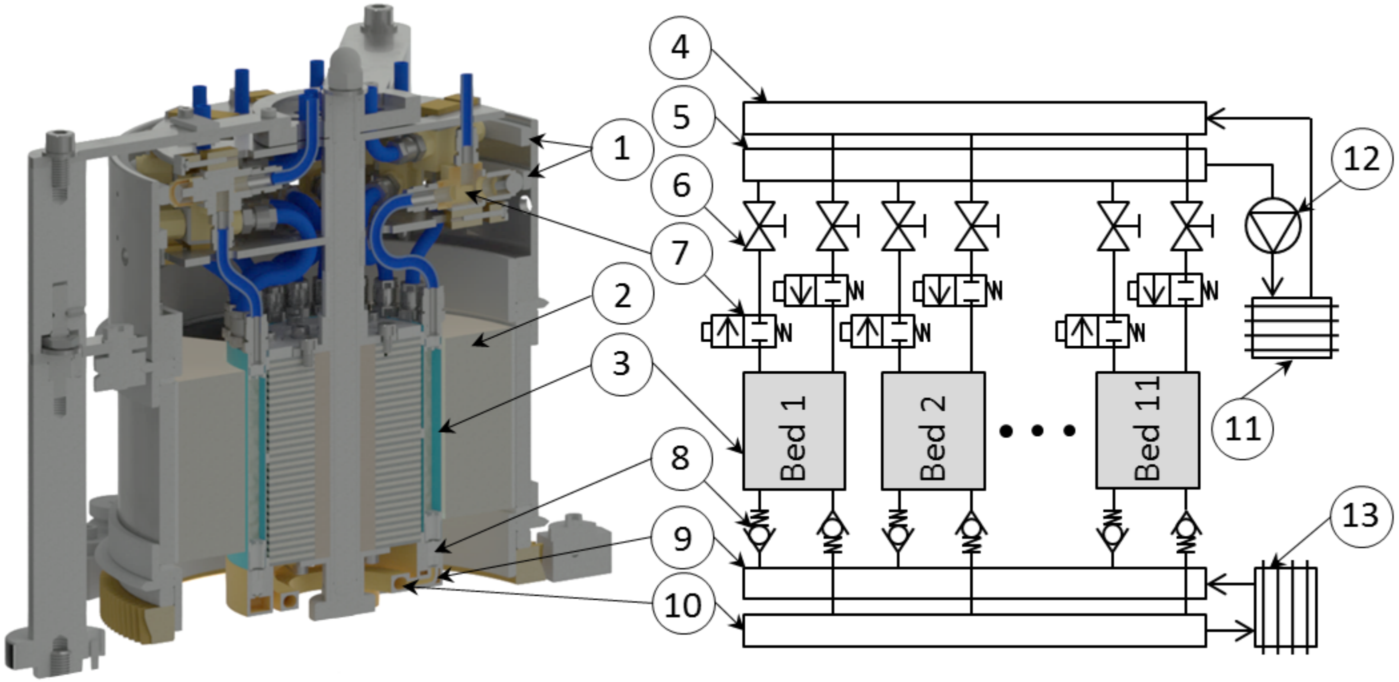
An unexpected phenomenon



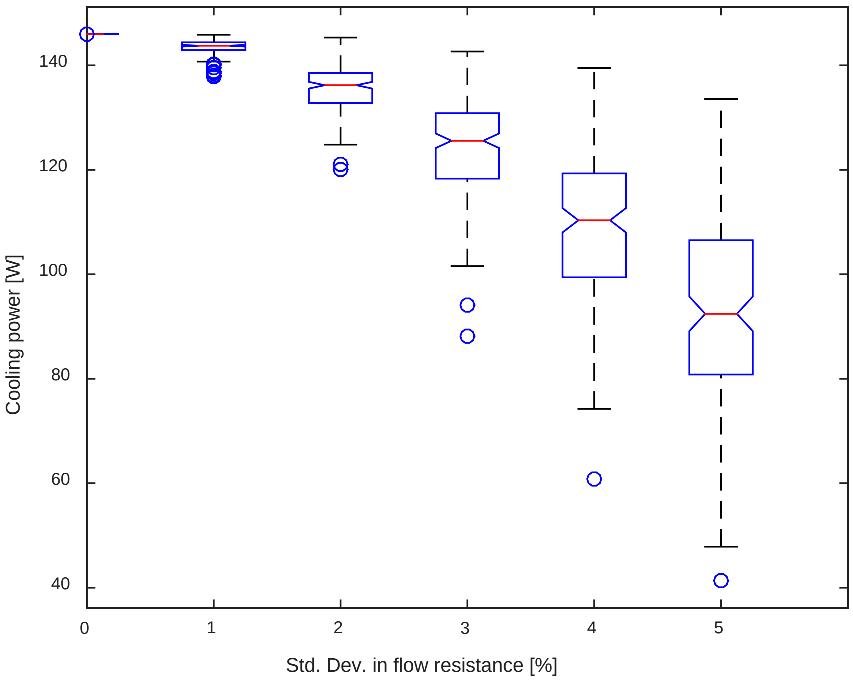
Adjustment of one out of the 22 valves can greatly impact performance

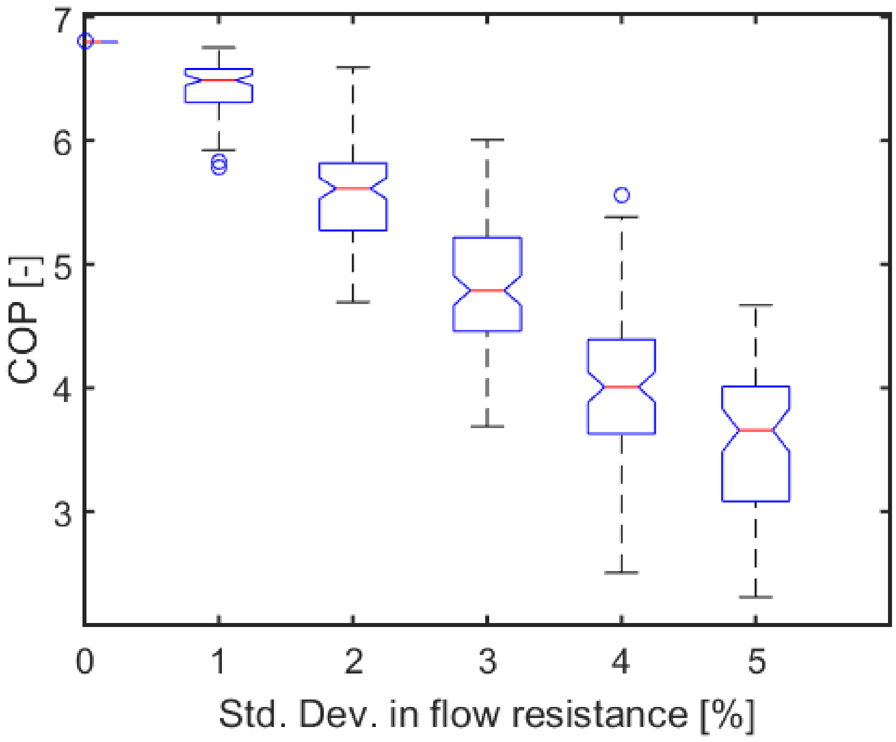
Flow balancing in multiple regenerator AMRs

- Total flow into and out of the regenerator is equal.
- In each individual bed, it is possible to have a slightly different flow rate in each flow direction
- Distributions of regenerators with small variations in their flow resistance were modeled with our 1D numerical model



Flow imbalance effects on AMR performance





D. Eriksen et al., 2015, submitted to *Int. J. Ref.*

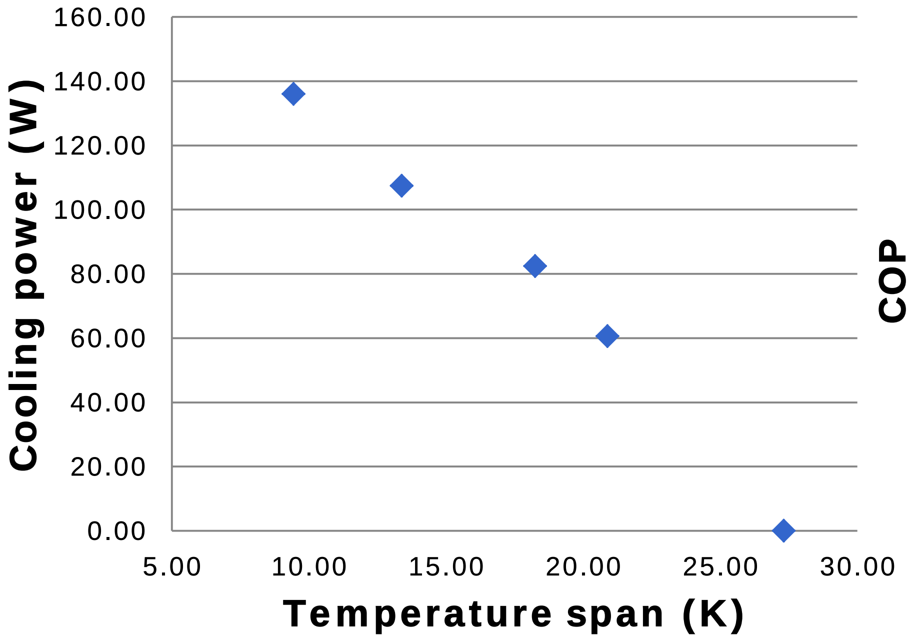
Flow balancing: main conclusion

- Flow resistance in each bed in both directions must be adjusted before experiments can be run (22 valves).
    - Best adjustment technique is yet to be determined

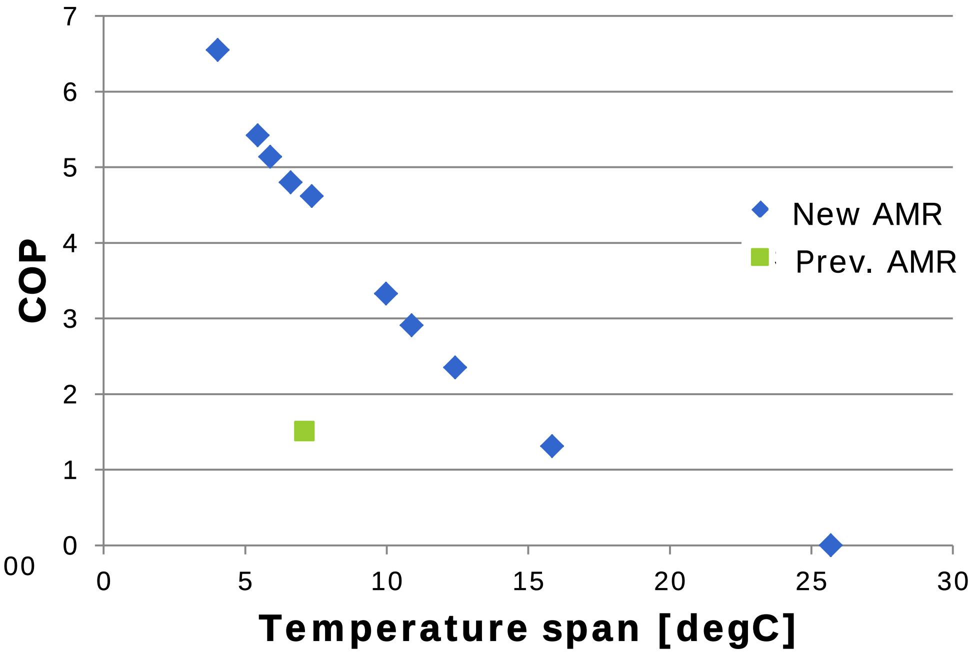
- All following results are for normalized flow resistances in each direction at a given fluid flow rate

Experimental performance

1 Hz operation 3 L/min flow rate



Improved COP demonstrated



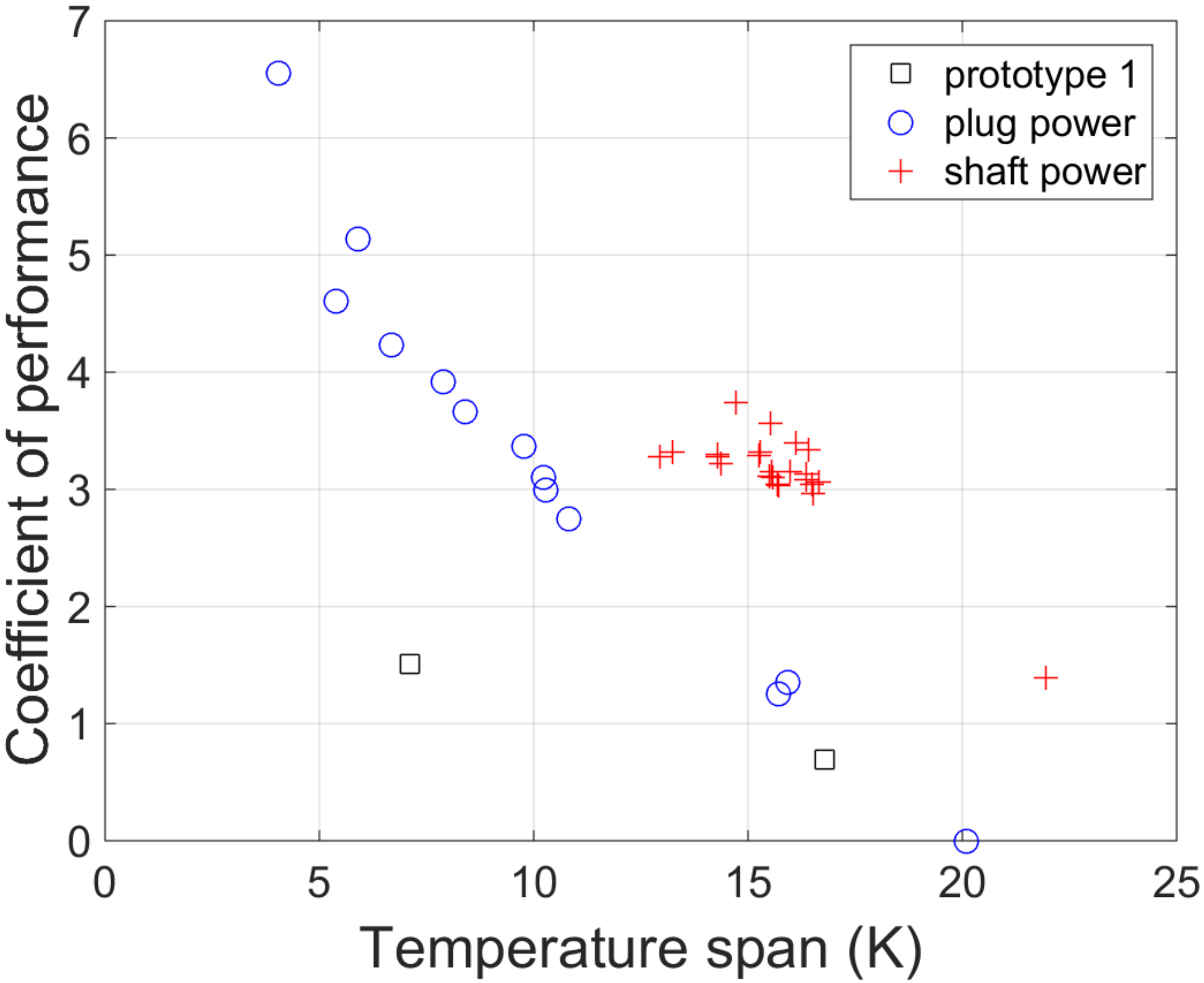
Improving efficiency measurements: shaft power evaluation

- Previous results were based on wall plug power measurements
  - Motor efficiency is not well known
  - Includes other parasitics such as motor controller

- A more reliable method is to report shaft power (Lozano 2015)
  - Expected actual efficiency can be calculated using the efficiency of the pump and motor

- Allows accurate assessment of parasitic losses such as bearing and valve drag

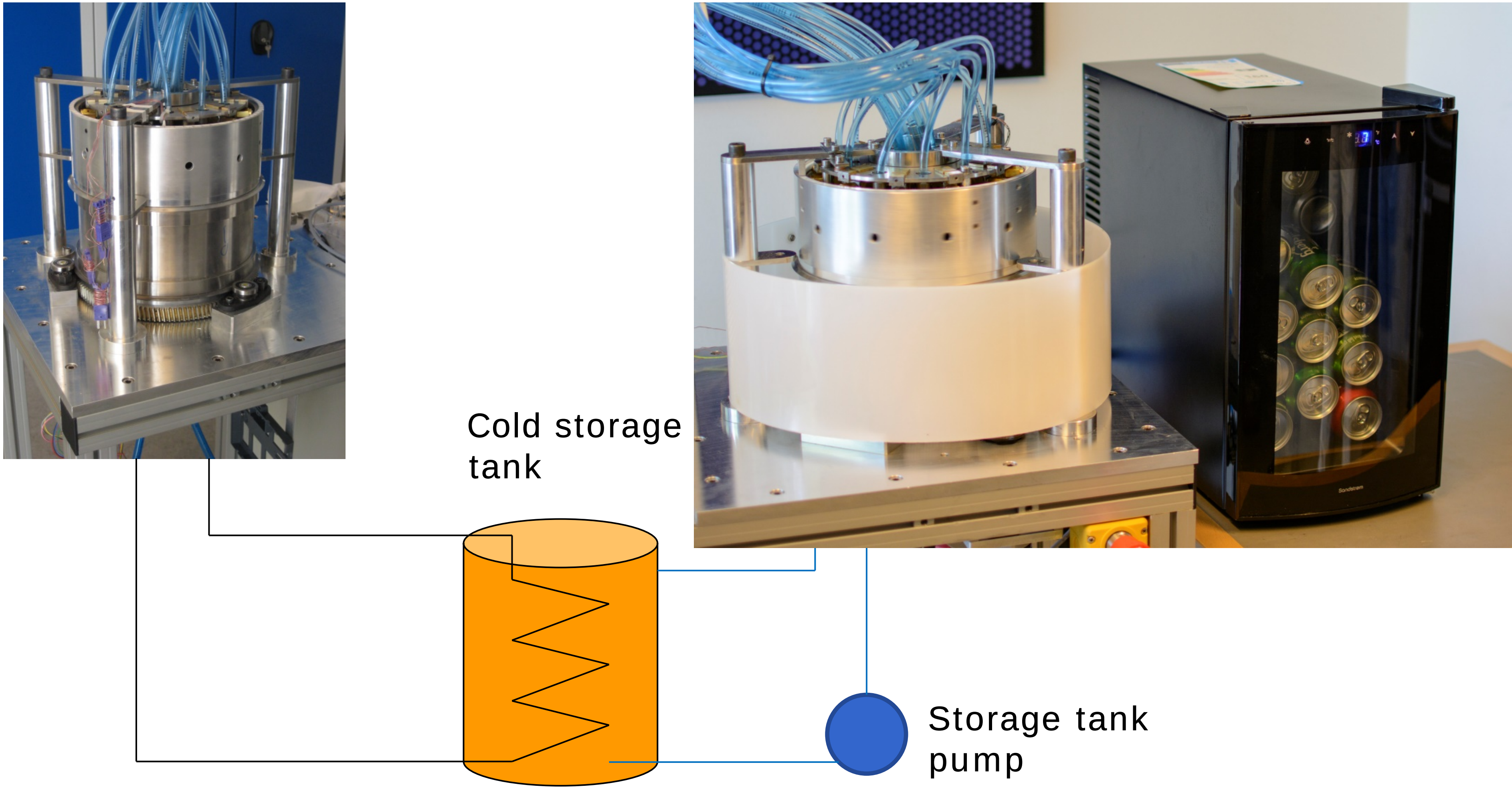
COP measurements for shaft work



Performance highlights to date

- Maximum temperature span 29.2 K @ 1.4 Hz and 3.4 L/min fluid flow
- COP of 3.32 (shaft power) with cooling power of 82 W and 15.3 K temperature span @ 1.0 Hz and 2.5 L/min fluid flow
- Maximum cooling power so far is 160 W at a temperature span of 5.5 K @ 0.47 Hz and 3.8 L/min fluid flow
- Full characterization has been delayed by flow system adjustment, minor component failures and component optimization

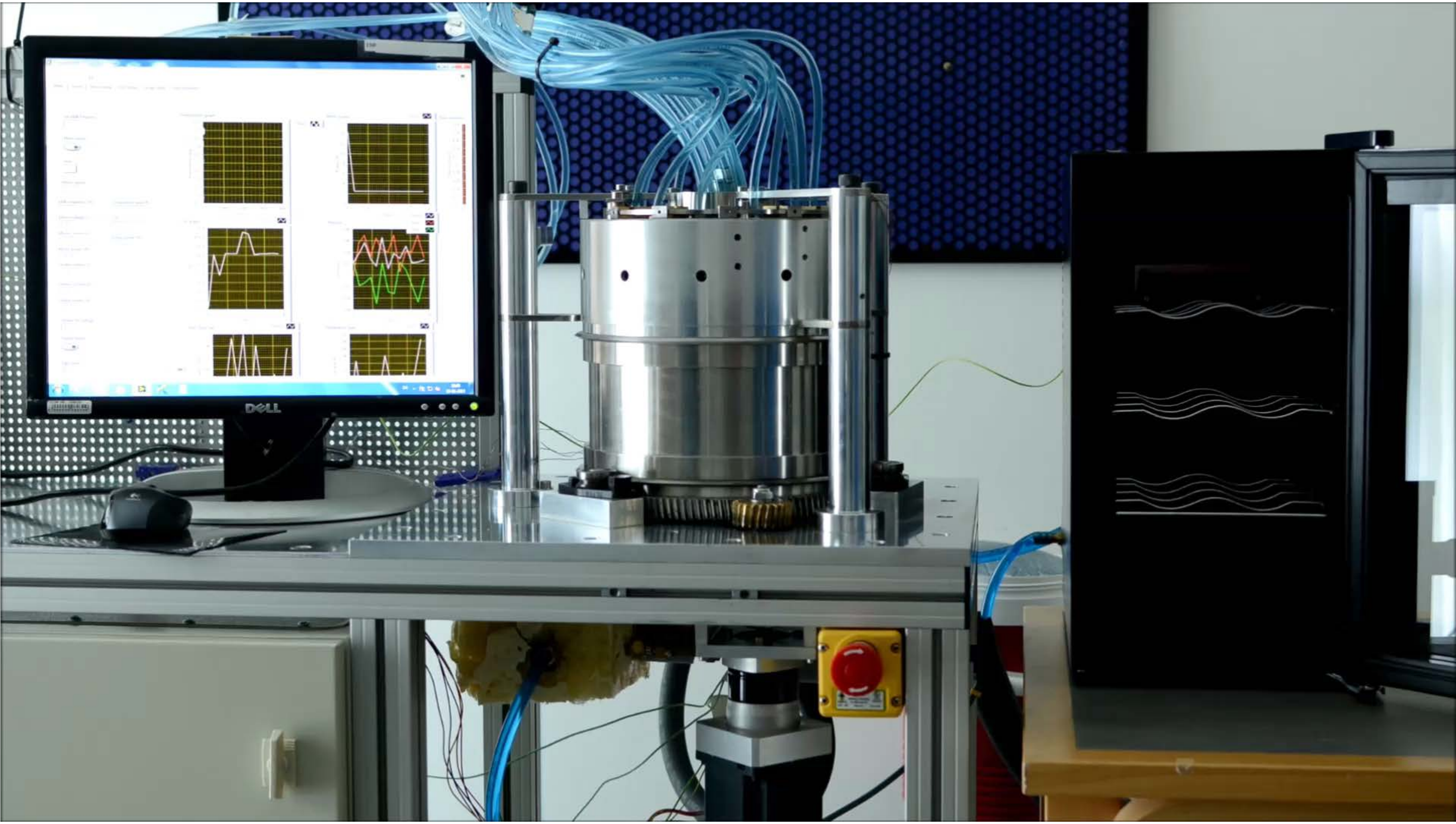
Incorporating thermal storage



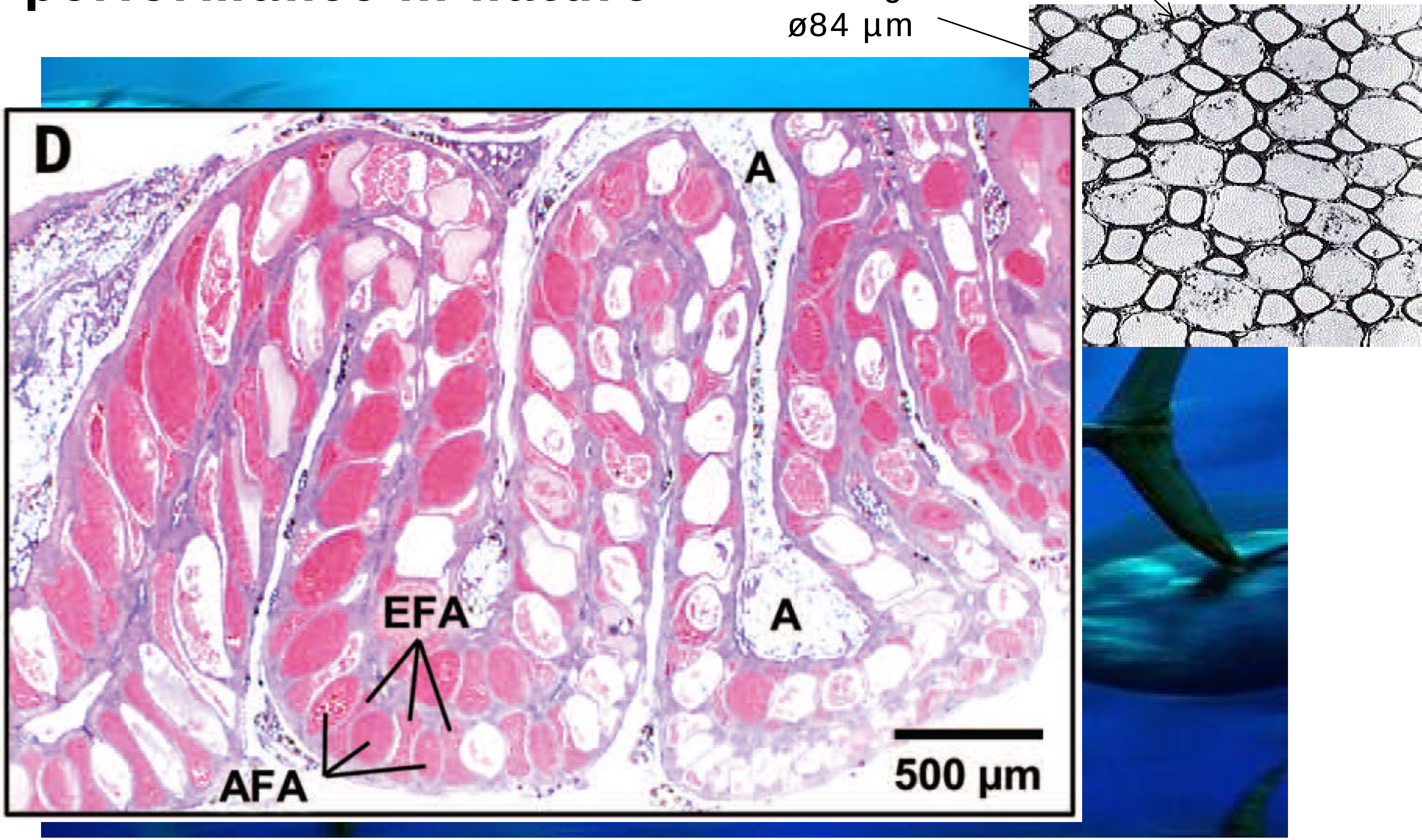
Cold storage tank

Storage tank pump

Operating with thermal storage



Examples of high thermal performance in nature

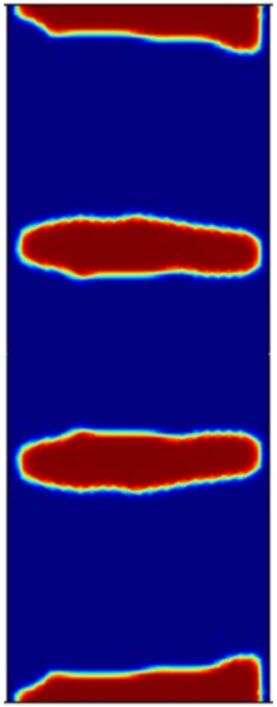


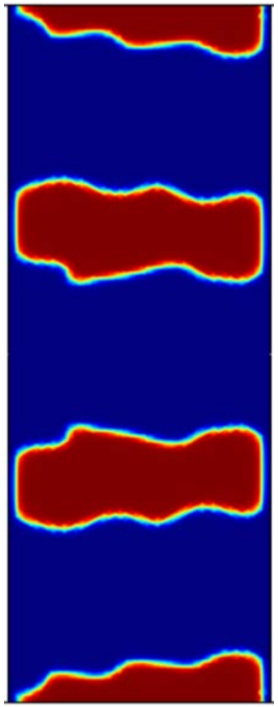
Average ø84 µm

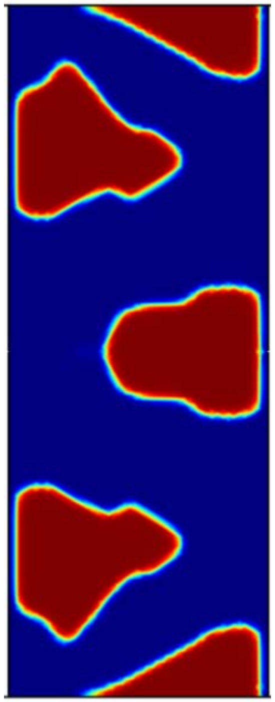
Average ø36 µm

Topology optimization of a heat sink


0.01 Pa


0.1 Pa


0.5 Pa

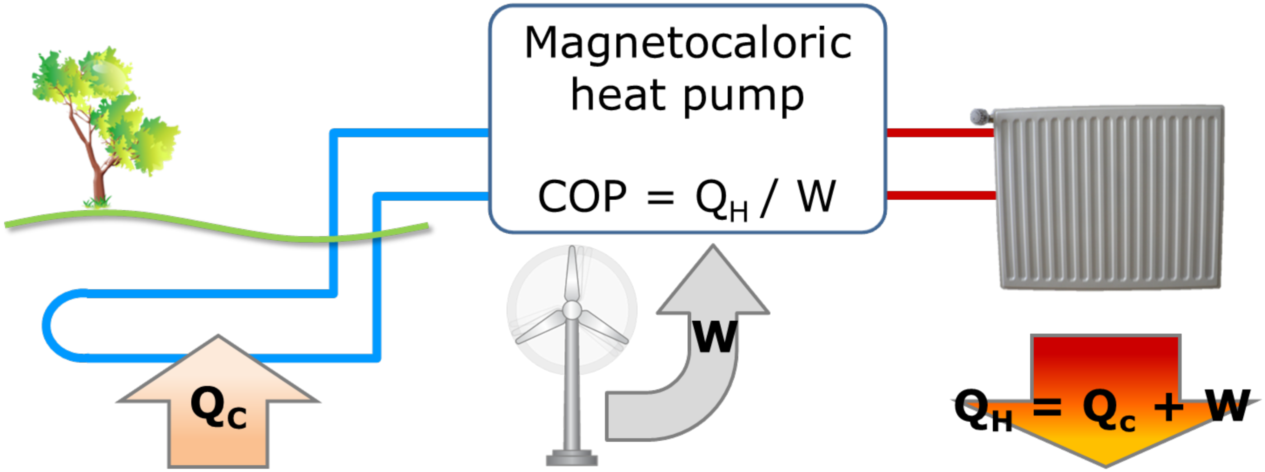

1.0 Pa

→ More and bigger fins with increasing Δp

→ Bumps on fins increase with increasing Δp

Concept of a magnetocaloric heat pump

- **2 kW** is approximately the required heating power for a normal house in the 2015 Danish building code for energy use. A temperature span of the order of **30 K** and a **COP of 5** would make a competitive heat pump.
- In a water-to-water heat pump the secondary heat exchangers may not be necessary.
- The heat pump can run on renewable energy sources, such as wind.

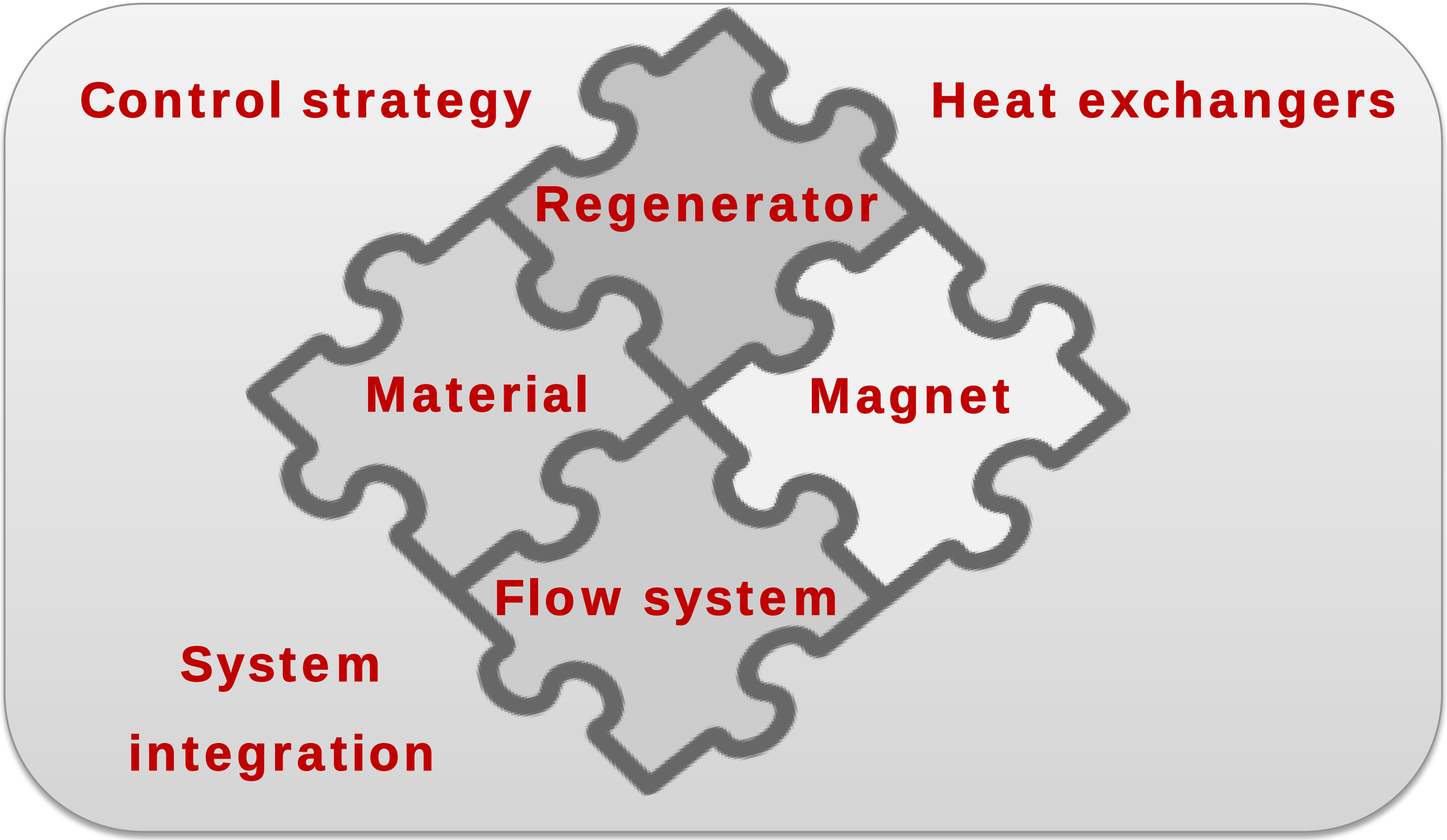


Magnetocaloric heat pump

$COP = Q_H / W$

Building a Magnetocaloric device

- Everything has to fit together – also the external parts.



Control strategy

Heat exchangers

Regenerator

Material

Magnet

Flow system

System integration

ENOVHEAT goals and highlights (see poster session)

- Studied the effect of variability in Curie temperature for a cascaded regenerator
- Studied effects of having a variable cross-section of the regenerator
- Studying techniques to reduce magnet volume
- Design of an improved efficiency device (used for a heat pump)
- Develop building integration techniques and control strategies

Conclusions

Compact rotary AMR prototype was designed and built

- COP is more than double compared to previous device while maximum temperature span is increased by ~4 K
  - Better magnetic force balancing
  - Low friction / no internal leakage valve system
  - Improved flow control
  - Layered regenerator bed
- COP reported for shaft power rather than wall plug power
- Controlling flow imbalance in each regenerator bed is fundamental to attaining high performance in multi-regenerator AMRs
- Thermal storage concept demonstrated but more experimental/analysis work needs to be done
- Full experimental characterization remains a future task

THANK YOU FOR YOUR ATTENTION

The AMR as a smart device

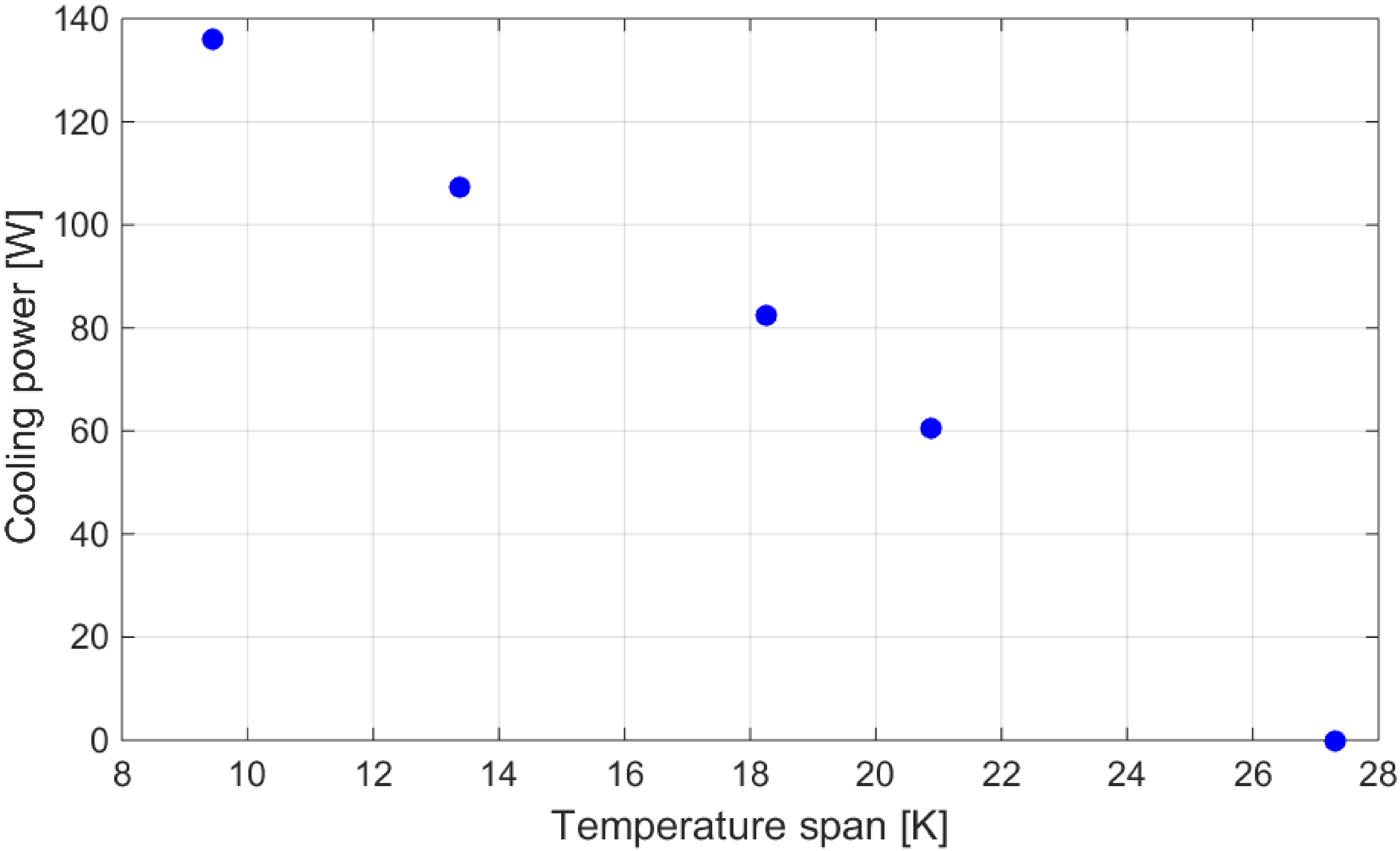
From Per Lundqvist’s keynote talk at ICR2015 “The role of heat pumps in the smart energy system”

- All devices need to be smart
- Heat pumps will be a necessary part of the smart electricity grid and smart thermal grid
- Heat pumps are an “enabling technology” for renewable energy

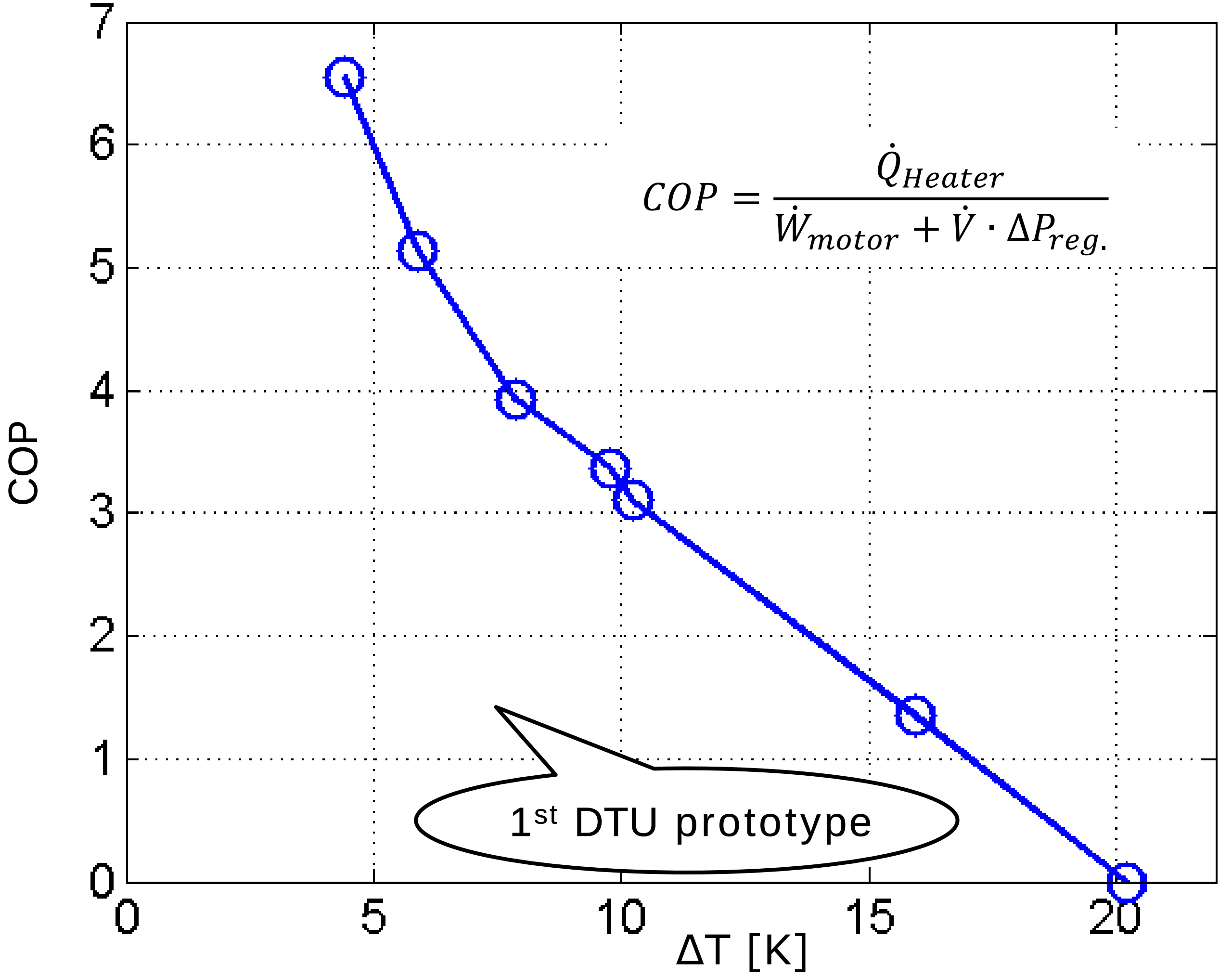
- AMR heat pumps meet the requirements for smart heat pumps
  - Can communicate with external systems
  - Variable cooling power/operating conditions
  - Can be coupled to thermal storage

- Single phase fluid may be more practical for smart applications

Some initial experimental results



COP, preliminary results



$$COP = \frac{\dot{Q}_{Heater}}{\dot{W}_{motor} + \dot{V} \cdot \Delta P_{reg.}}$$