A high frequency rotary active magnetic regenerator device

Kurt Engelbrecht, Christian Bahl, Dan Eriksen, Rasmus Bjørk, Kaspar Nielsen, Nini Pryds
Risø DTU
National Laboratory for Sustainable Energy

David Velázquez
Instituto de Ciencia de Materiales de Aragón (ICMA), CSIC
Zaragoza University, Spain

Jaime A. Lozano
POLO Research Laboratories, Federal University of Santa Catarina (UFSC), Florianópolis, Brazil

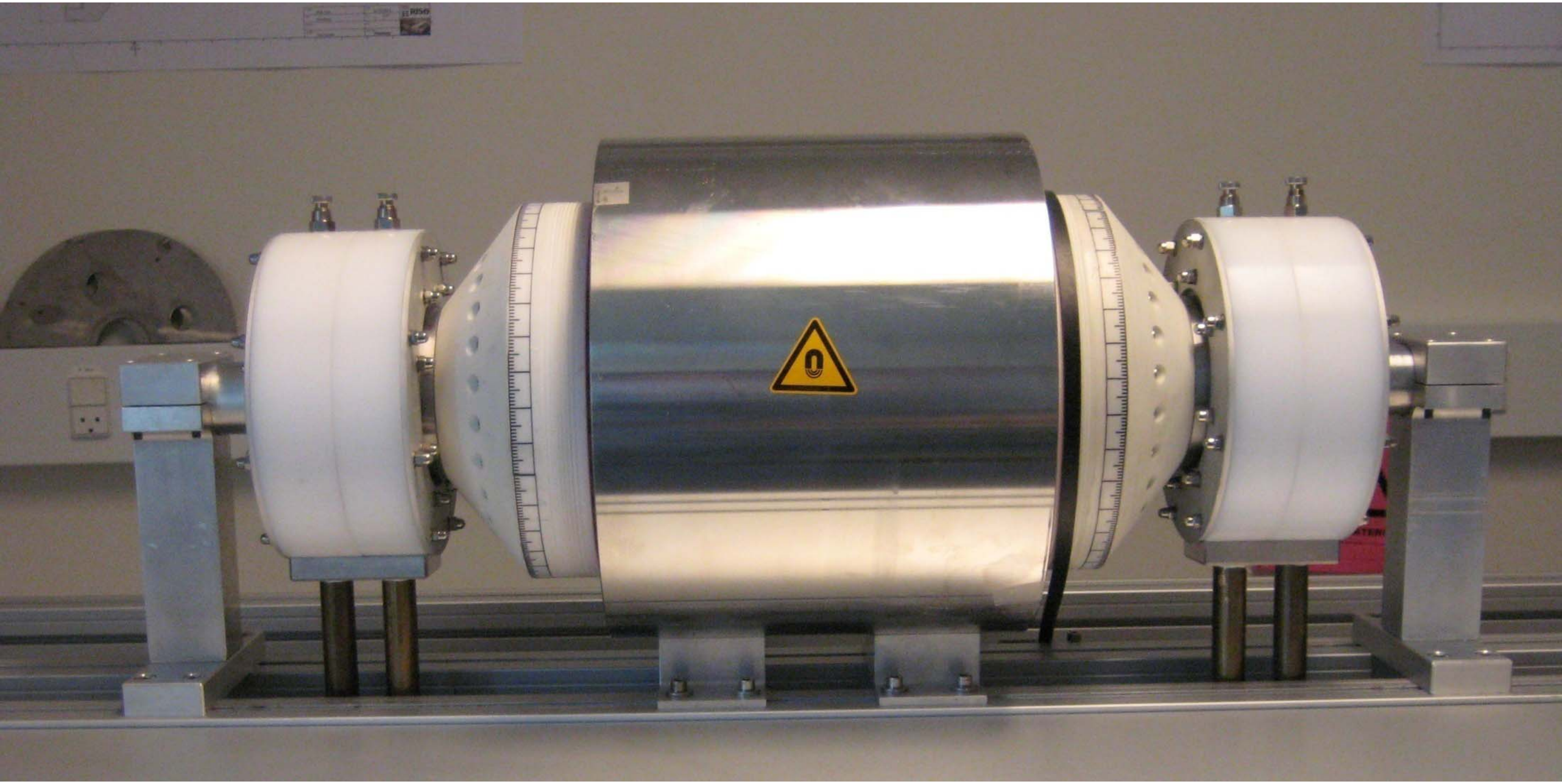
Outline

- Design and construction of a rotary AMR device
  - Design of subsystems
- Machine issues / updates
- Experimental results
-

AMRR Loss Mechanisms

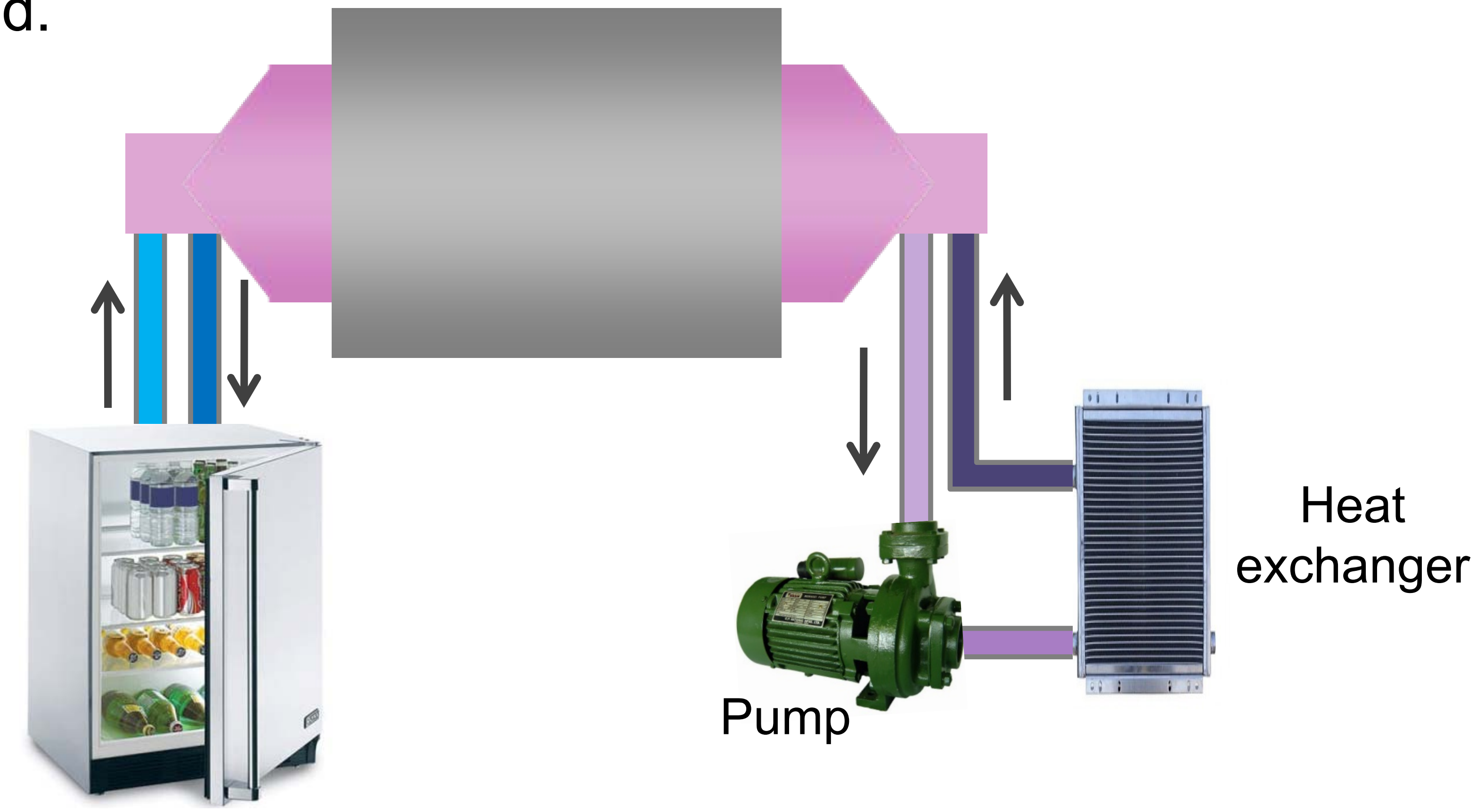
- Heat transfer / regeneration losses
- Pumping / viscous dissipation losses
- Axial conduction
- Eddy current heating
- Heat exchanger and motor losses
  - nominally equivalent to vapor compression

Risø AMR Design



Practical Implementation

- The flow circuit includes pump, heat exchanger and heat load.



AMR System Components

- Magnetocaloric material
- Magnet
- Flow system
- Regenerator

Choice of magnetocaloric material

- Many materials are available. None are optimal in all parameters so the choice is difficult.

- Gadolinium
    - *High magnetocaloric effect*
    - *Expensive but commercially available*
    - *Processing into plates increases the price more than 10 times*

- Spheres sieved to 0.25 - 0.8 mm

- The regenerator length was reduced to avoid excessive pressure losses while retaining high cooling power
    - 100 mm in flow direction
    - 2.8 kg total Gd mass

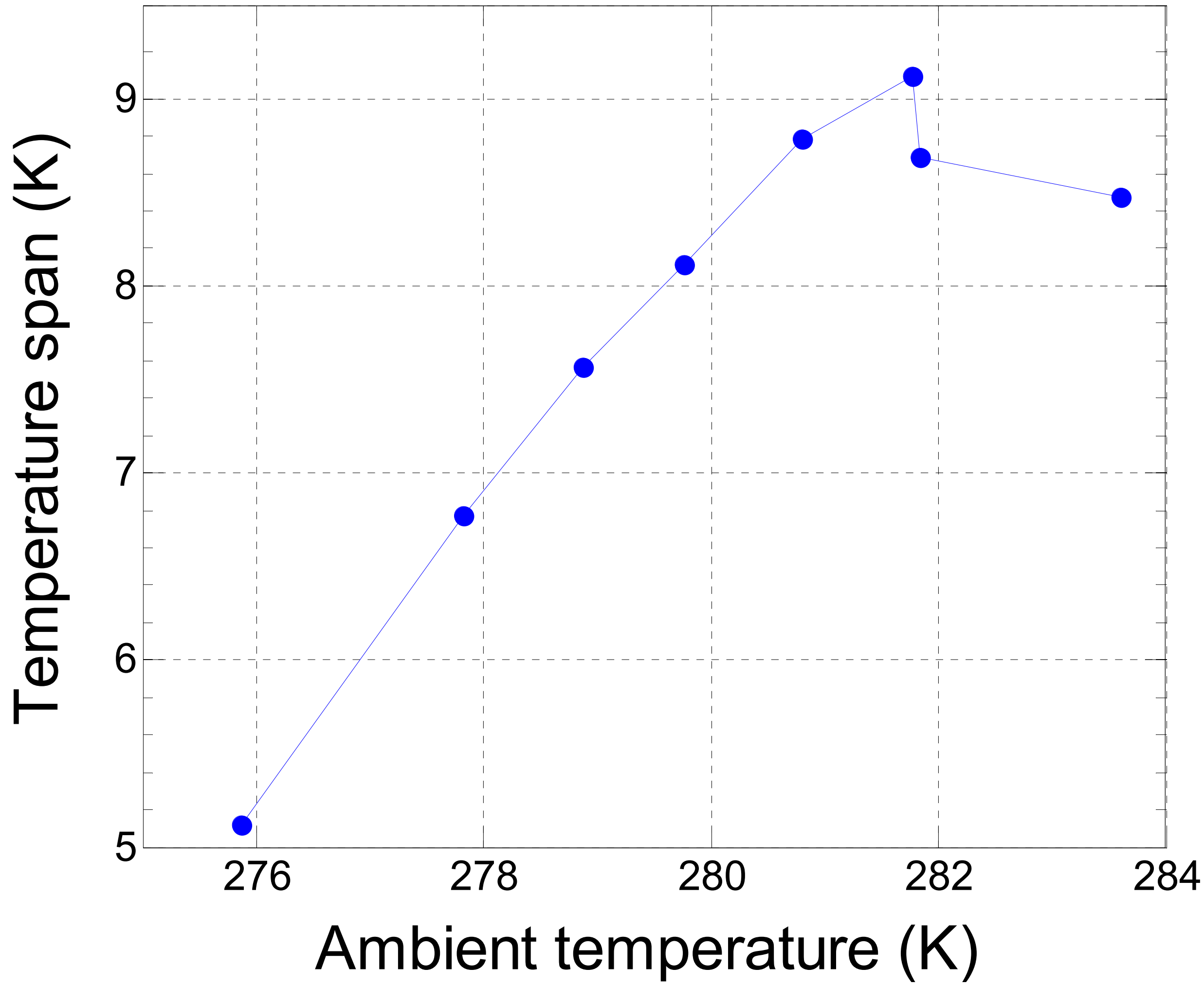
Alternate Materials - 1st Generation Test Device

- Field change from 0 to 1.1 Tesla
- Max operating frequency is 0.5 Hz
- Regenerator dimensions up to: 20x25 mm^2 cross-section with a length of 40 mm

Described in *International Journal of Refrigeration* 2011

Recent 2-Layer $La_{0.67}Ca_{0.33-x}Sr_xMnO_3$ Results

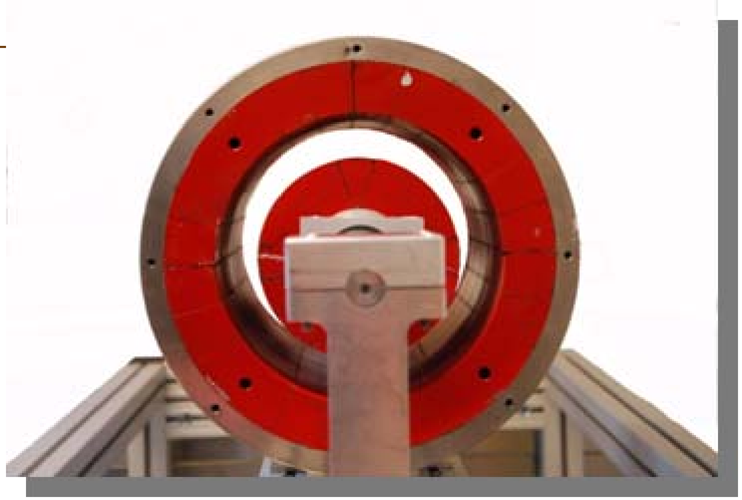
Utilization 0.51

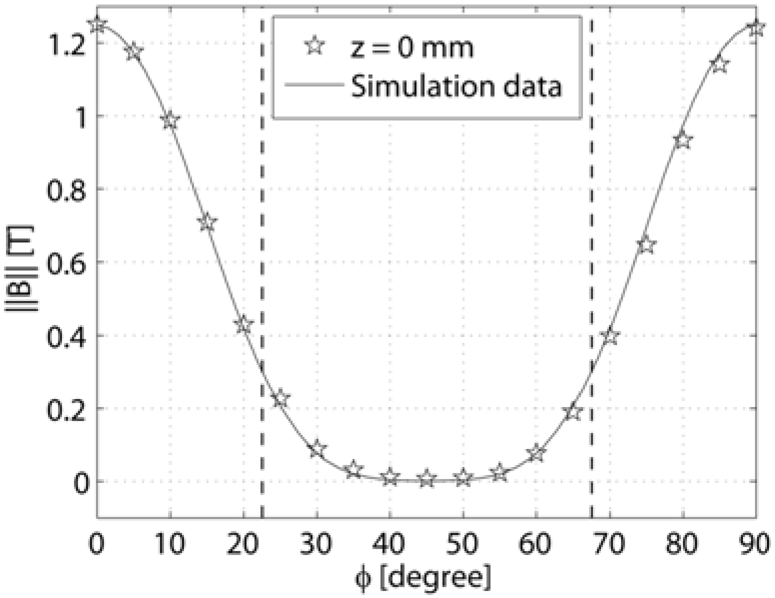


Realisation of the magnet design

- 7 liters of magnet material. 4 liters of regenerator volume.

- Good correspondence between model and measured values.



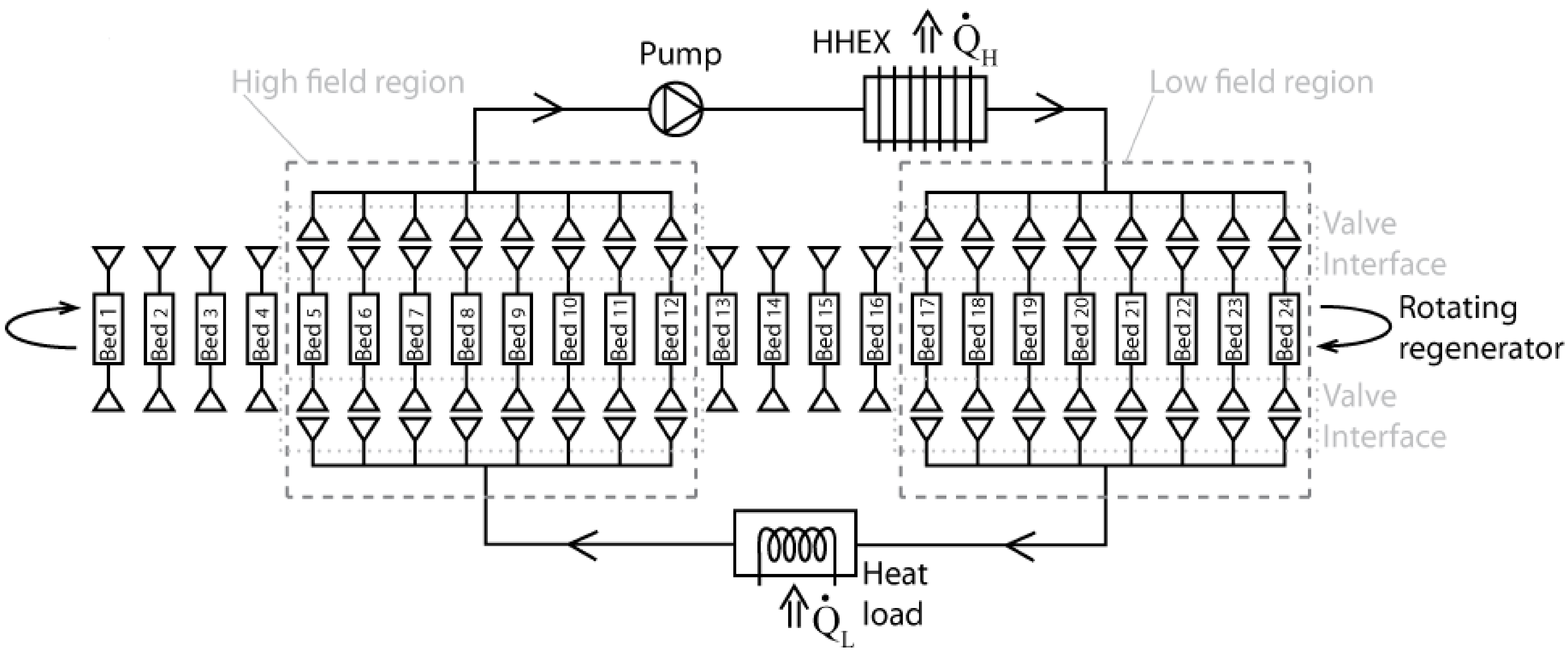


Bjørk et al., J. Magn. Magn. Mater. ***322*** *(2010) 3324*

Fluid Control System

- At all times, 8-10 regenerator beds in high field regions receive flow in one direction, 8-10 beds in low field receive flow in the opposite
- ”Dead volume” must be minimized to avoid losses (Jacobs, 2009)
- Seal friction and pressure loss external to the regenerator must be minimized

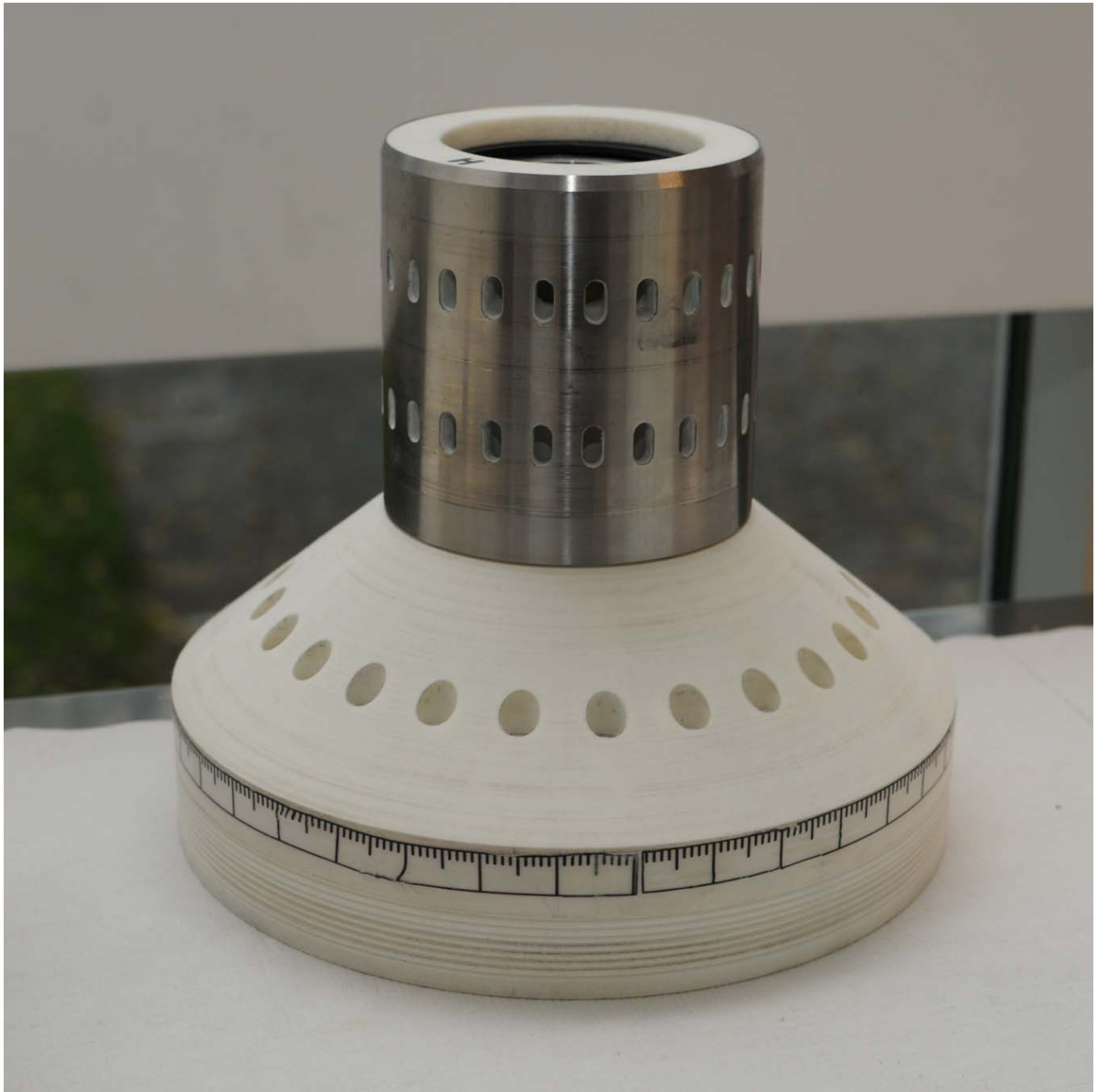
Fluid Control System



Valve Seal Design

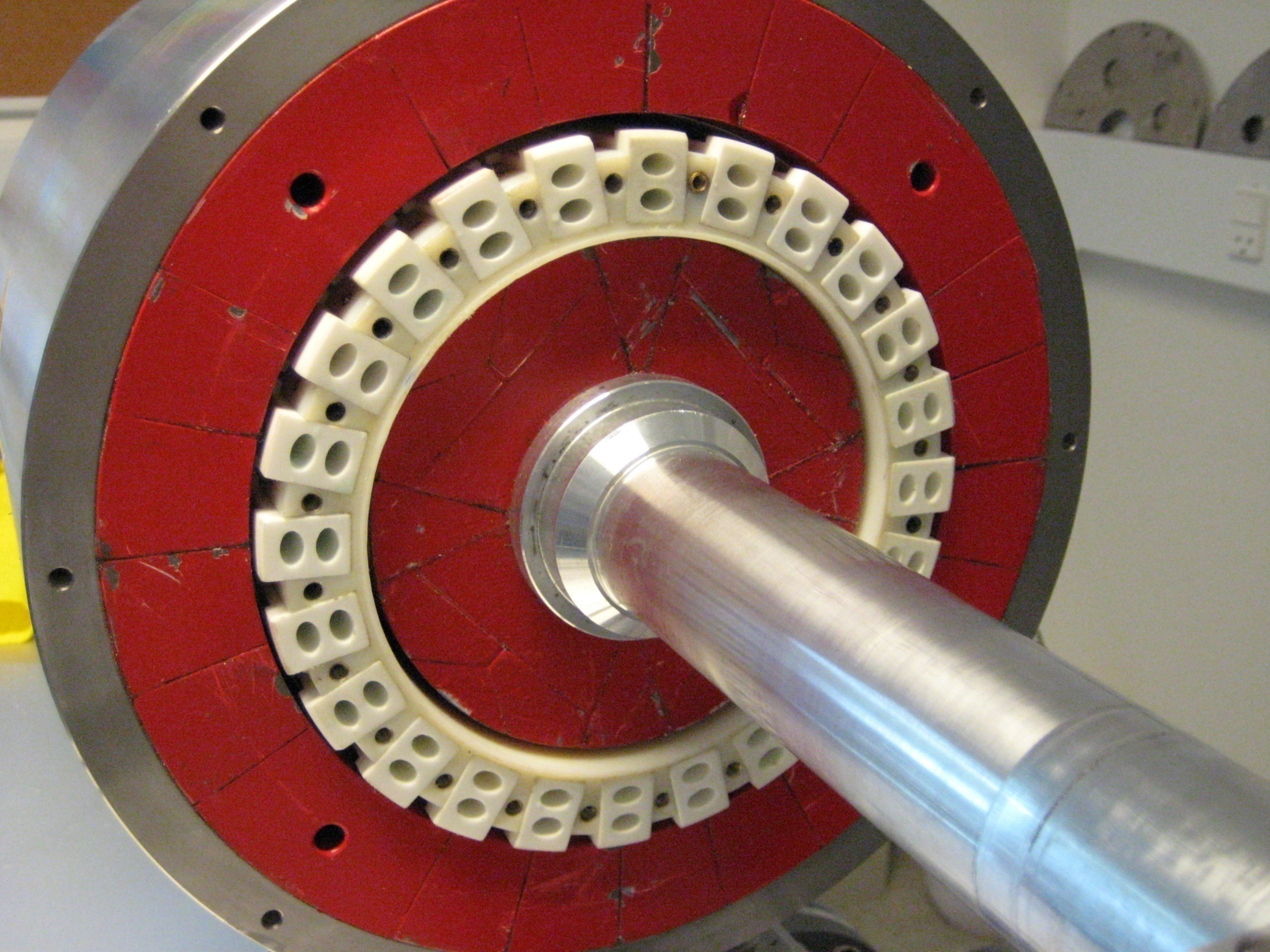
- Valve is HDPE on stainless steel
  - Low friction PTFE radial seals
- HDPE has a coefficient of expansion that is much higher than stainless steel
- Sealing surface is reduced from 140 mm & 200 mm to 105 mm
- Valve and seal friction may still be significant, especially at higher rotation speeds

Fluid Distributor

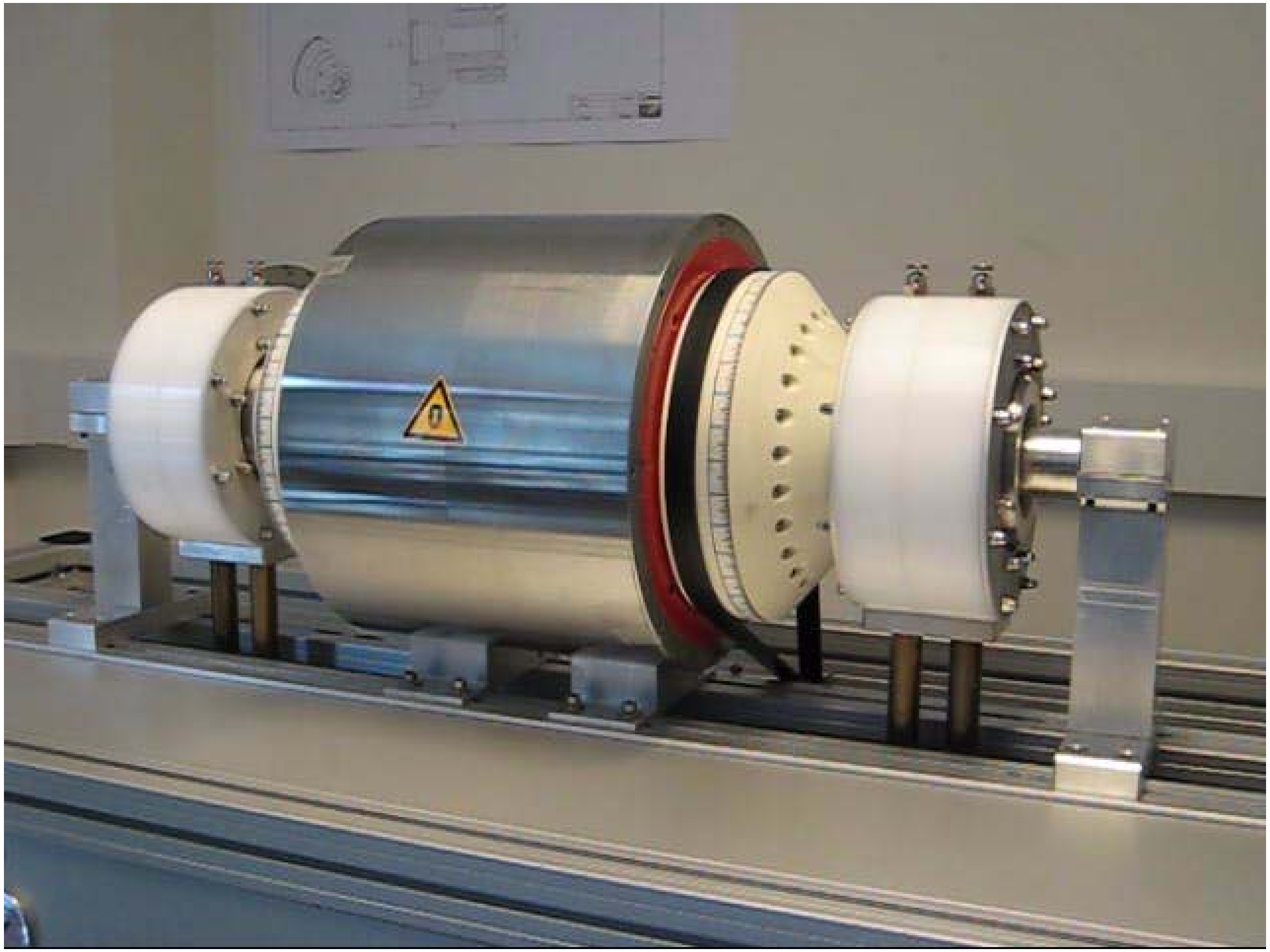


Regenerator

- Regenerator design focused on achieving even flow distribution in each bed
- To avoid eddy current losses, plastics were used wherever possible
- For flexibility and maintenance, each regenerator bed is removable
- Flow channel is 12.8 x 18.6 mm^2 in cross-section and 100 mm in the flow direction (24 cm^3 per bed)



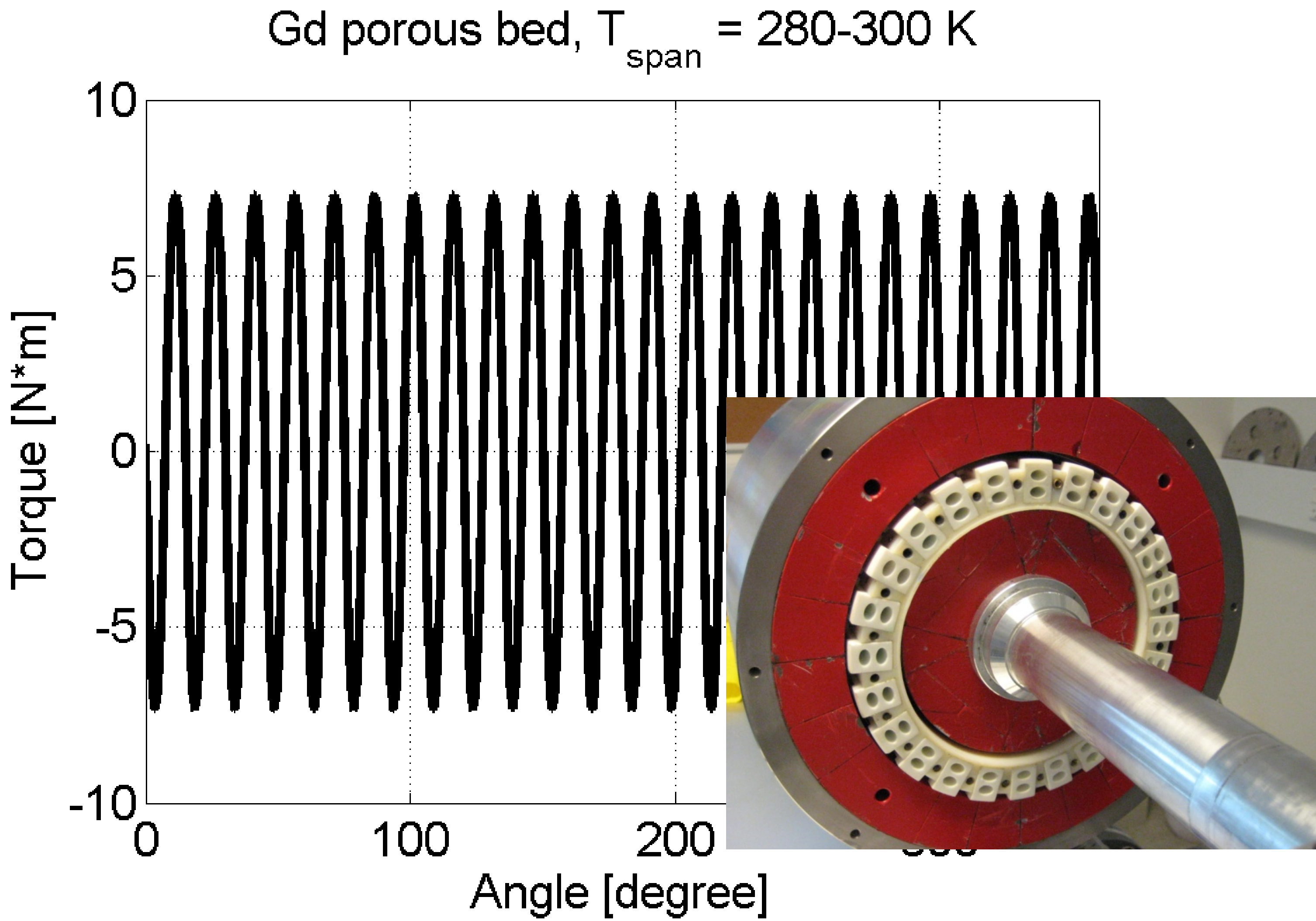
Prototype



Machine Problems

- 4 pole magnet and 24 bed regenerator result in uneven torque to rotate the regenerator
- Thermal expansion of the valve materials can cause high friction at higher temperature spans
- Heat generated in radial shaft seals

Torque Required to Rotate the Regenerator

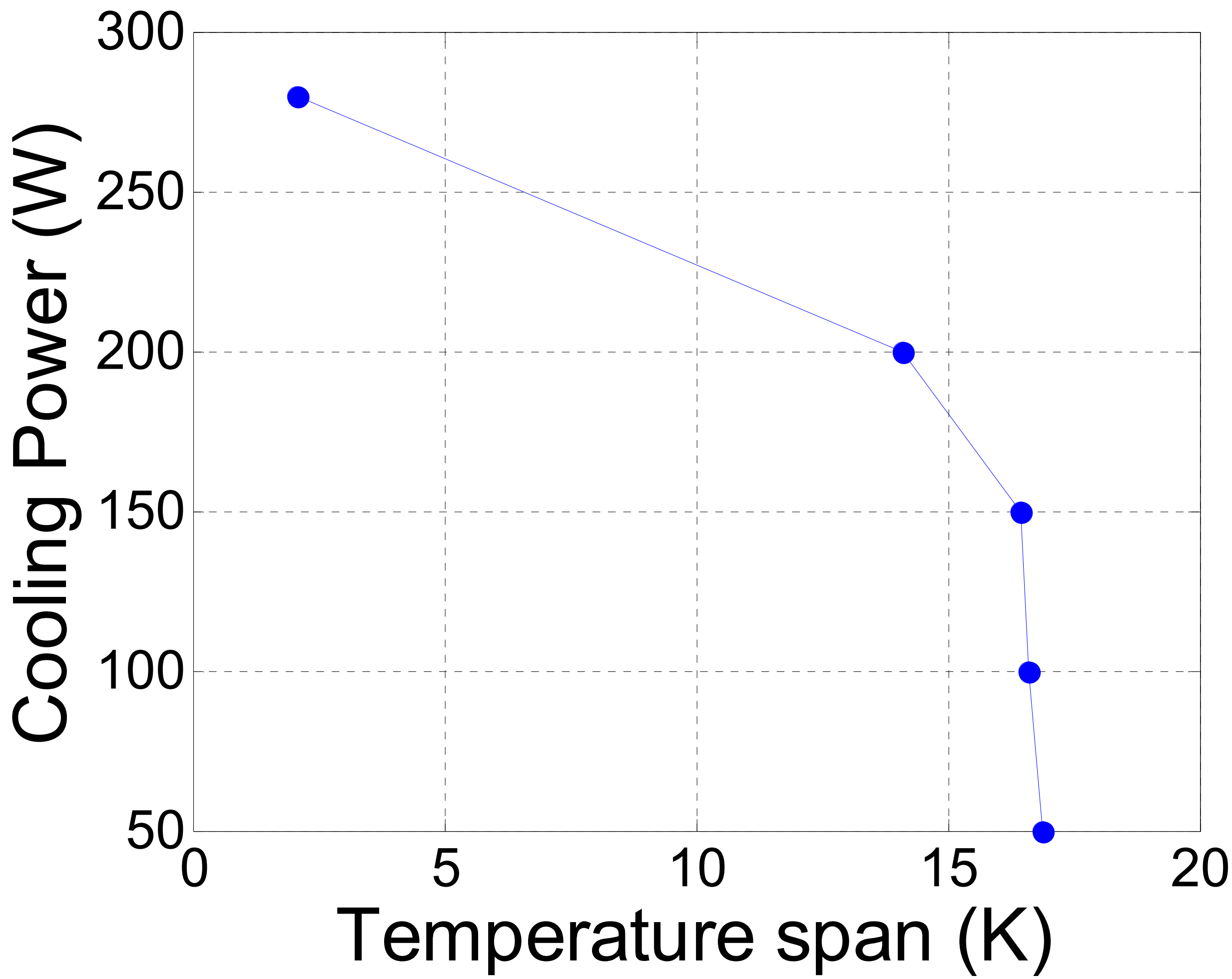


Recent Machine Updates

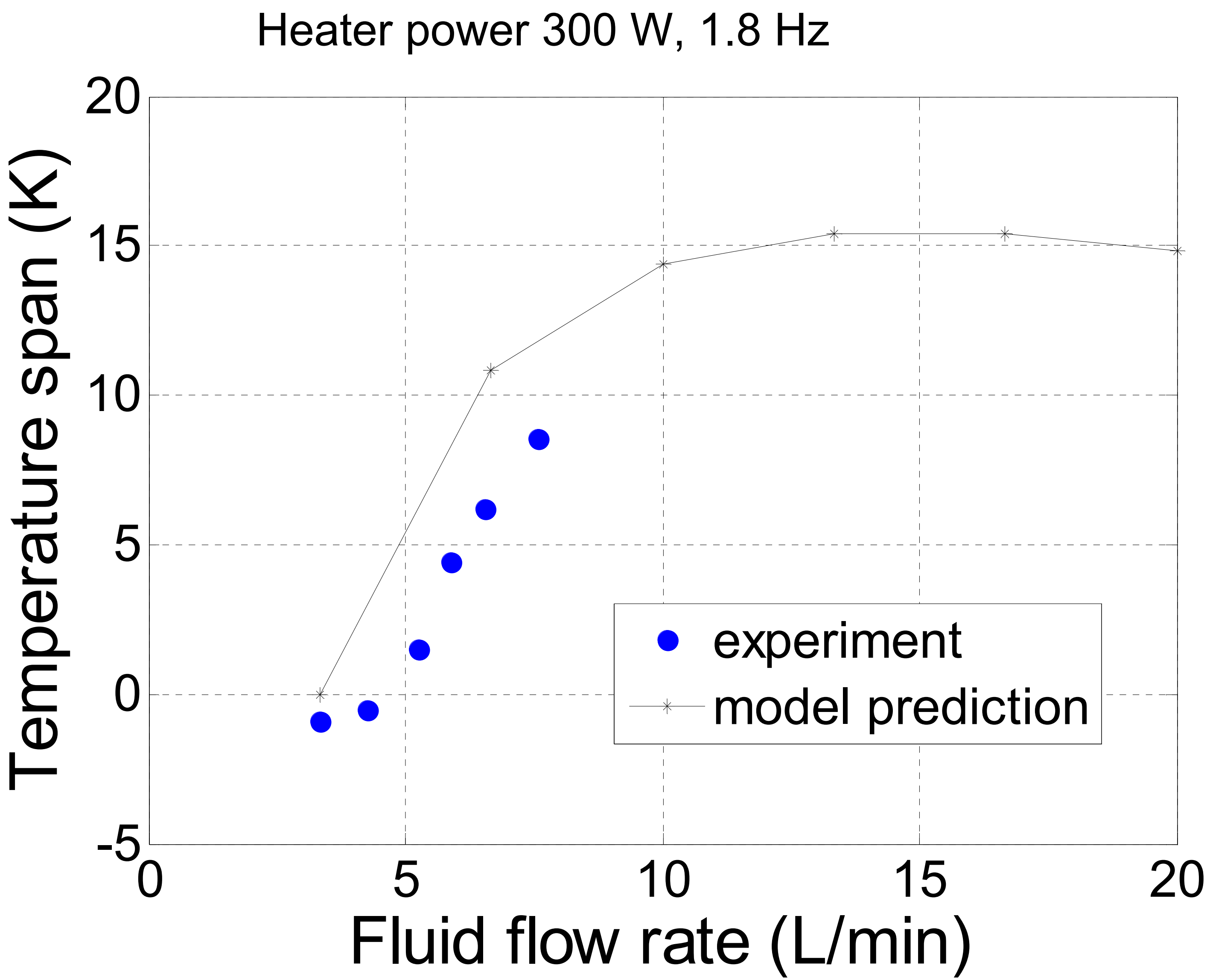
- New flow valves
  - Stainless steel / HDPE construction gives ~0 CTE
  - Lower dwell ratio
- New belt implementation
  - Increases maximum torque but not enough

Constant Presure Drop Experiments

ΔP = 1 bar (per bed) Fluid flow rate ~100 L/hr (1.7 L/min), 1 Hz, T_H = 302 K



Load Experiments (old valve)



More Experimental Results

Old valve

Flow rate (L/min)	TC (K)	T_{amb} (K)	T_H (K)	T_{span} (K)	Q_{heater} (W)
7.6	291.4	297.7	299.9	8.5	324
8.3	297.2	296.9	300.1	2.9	498
10.4	288.7	297.6	291.8	3.1	746
11.4	291.9	297.6	292.3	0.3	1010

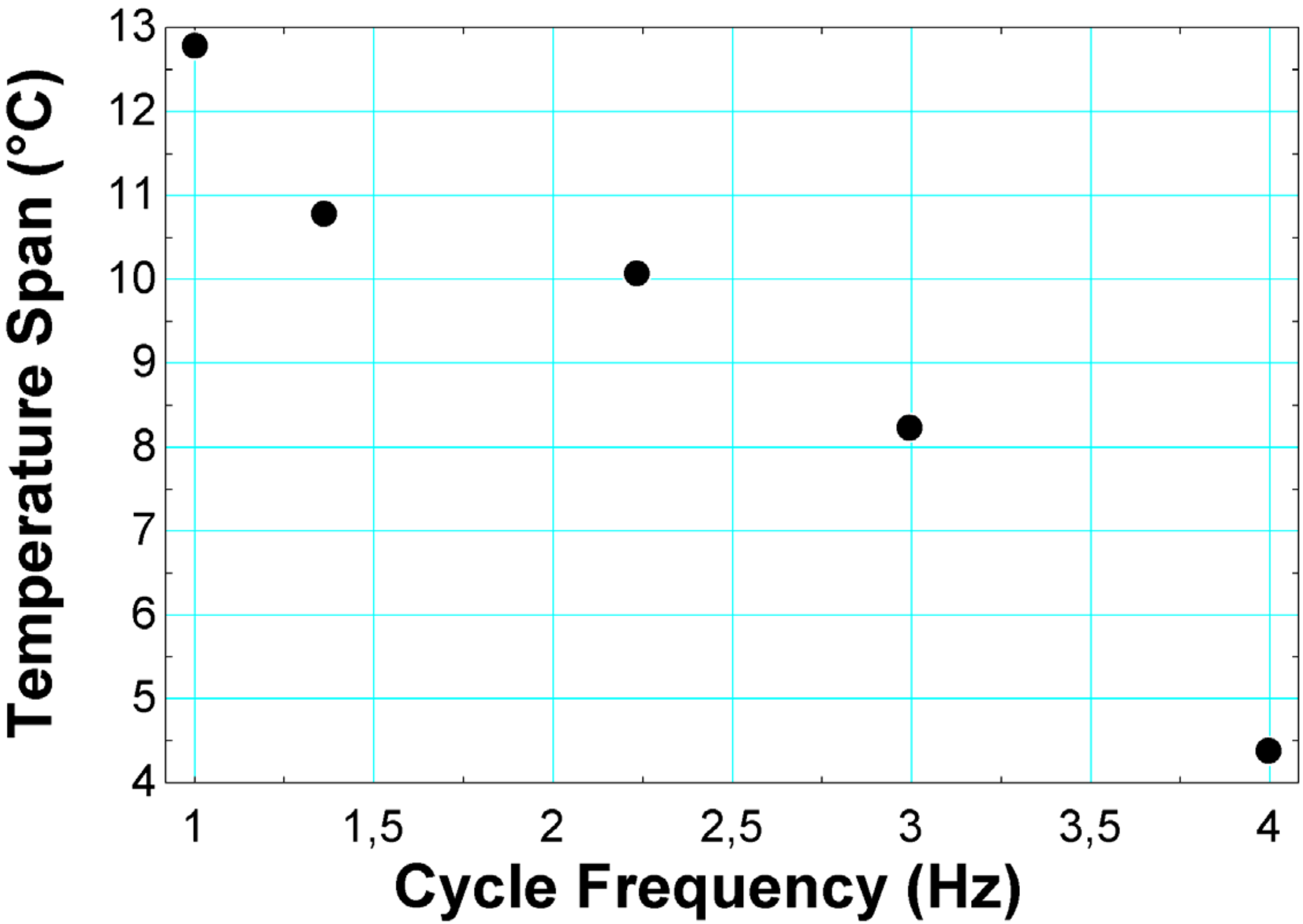
- Maximum temperature span for this device is 24 K (new valve)

High Frequency Experiments

- Maximum frequency is 8 Hz
- Heat geneation in rotary seals and valves is proportional to frequency
  - Friction losses estimated as
- Eddy current heating increases with increasing frequency

Initial Results – Varying Frequency

Fluid flow rate of 3.3 L/min



High Frequency Considerations

$$U \sim \frac{\dot{m}_f \, c_f}{f \, m \, c_{B,s}}$$

$$NTU = \frac{h \, A_s}{\dot{m}_f \, c_f}$$

$$NTU \sim \frac{h \, A_s}{U \, \boxed{f} \, m \, c_{B,s}}$$

Conclusions

- A rotary regenerator AMR experimental machine has been built and shown to produce a temperature span above 24 K
- Maximum measured cooling power is over 1000 W at ~0 K span
- The design in modular and testing additional regenerator geometries and materials is straightforward
- Operating frequencies up to 8 Hz are possible but require higher performance regenerator geometry

Model Extrapolations

- Max no-load temperature span at 2 Hz ~27 K at 6.7 L/min fluid flow

- Machine should produce 800 W at a temperature span of 10 K with a flow rate of 20 L/min

AMRR Design Consideration

- The mass flow rate of fluid in an AMRR is much higher than an equivalent vapor compression system
  - no phase change in the fluid

$$\frac{\dot{m}_{AMRR}}{\dot{m}_{vc}} \sim \frac{\Delta h_{v,ref}}{c_f \Delta T_{mc}}$$ for equal refrigeration capacity

- For a practical system, the fluid flow rate is ~20 times the refrigerant flow rate for vapor comp
- Requires larger connecting piping to reduce pressure drop

Regenerator Design

- Packed regenerator
  - packed sphere, packed powder, etc.
  - relatively easy to achieve high surface area
  - fluid flow profile is generally well-distributed
  - high pressure drop

- Flat plate regenerator
  - low pressure drop
  - requires small dimensions to achieve high heat transfer performance
  - theoretically best regenerator performance
  - performance highly dependent on geometry