Recent Developments in Room Temperature Active Magnetic Regenerative Refrigeration

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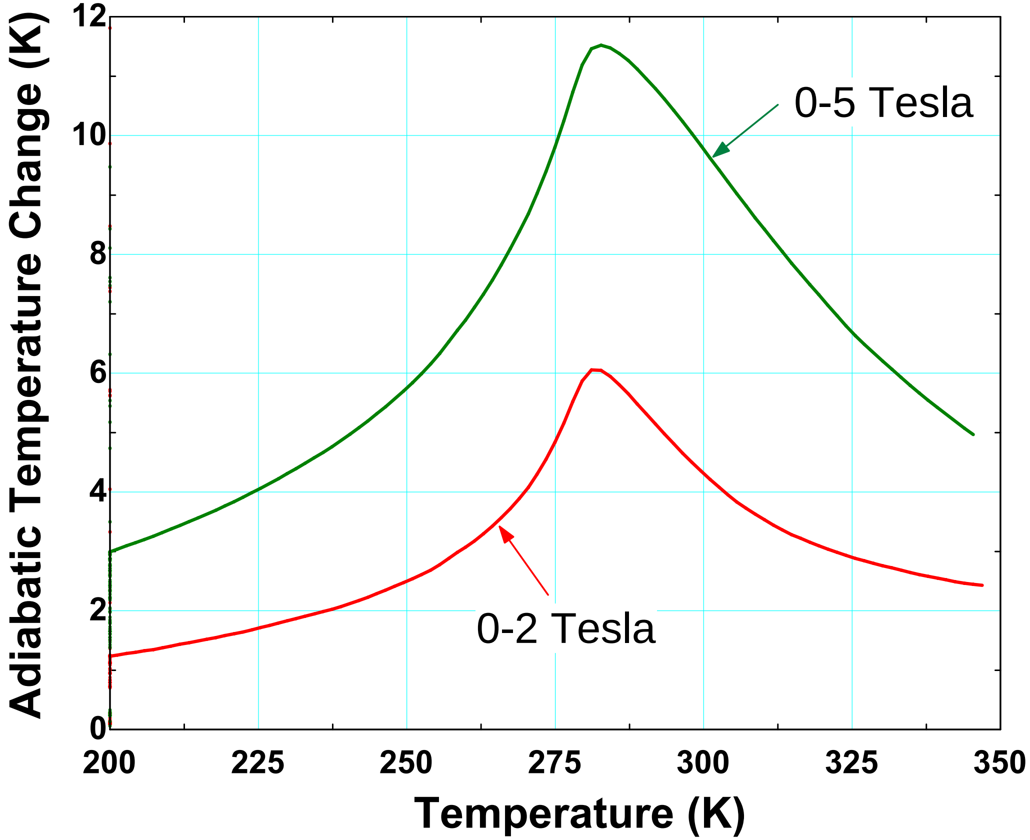
Magnetic Refrigeration Background

- Alternative to vapor compression
- Magnetic refrigeration used to first break 1K temperature barrier near 1935, but used a one shot technique with a very low temperature span
  - Giauque awarded the Nobel Prize in chemistry in 1949
- First regenerative magnetic refrigerator proof-of-concept device built by Brown in 1976
- Possible applications include residential/commercial space cooling, refrigeration, hydrogen liquefaction/storage

Advantages of Magnetic Refrigeration

- Environmentally friendly
  - no ozone depleting or direct global warming associated with the refrigerant
- Possibly more efficient than current technologies
  - no superheat or throttling loss
  - no compressor losses
  - nominally equivalent heat exchanger loss
  - relatively easy to achieve efficient part load operation
- Quiet operation

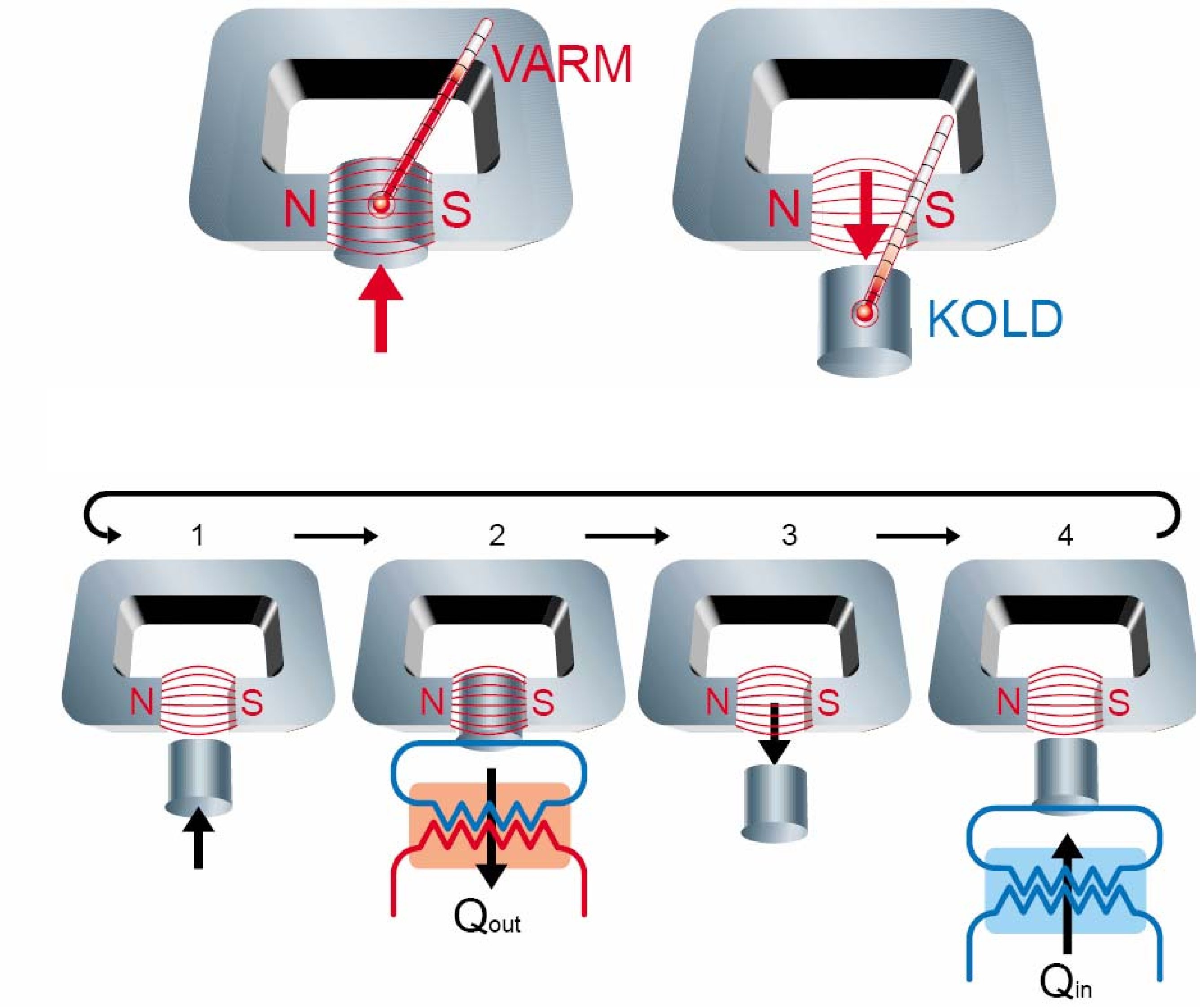
Room Temperature Magnetic Materials



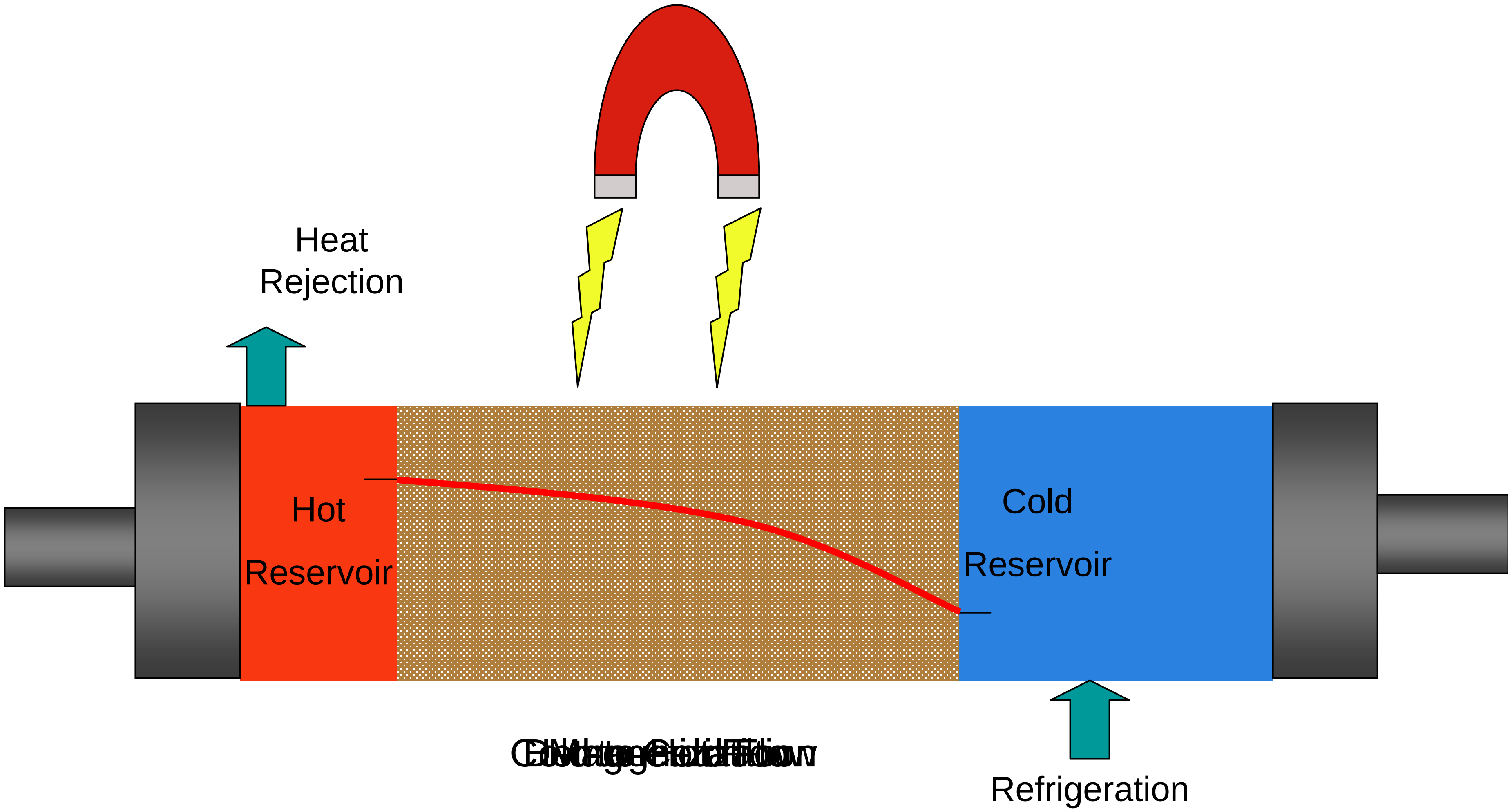
Gadolinium (Gd) and Erbium (Er) alloy

The magnetocaloric effect is greatest at the Curie point of the magnetic material, which can be adjusted by alloying

Magnetic Refrigeration Concept



Active Magnetic Regenerative Refrigerator Cycle (AMRR)

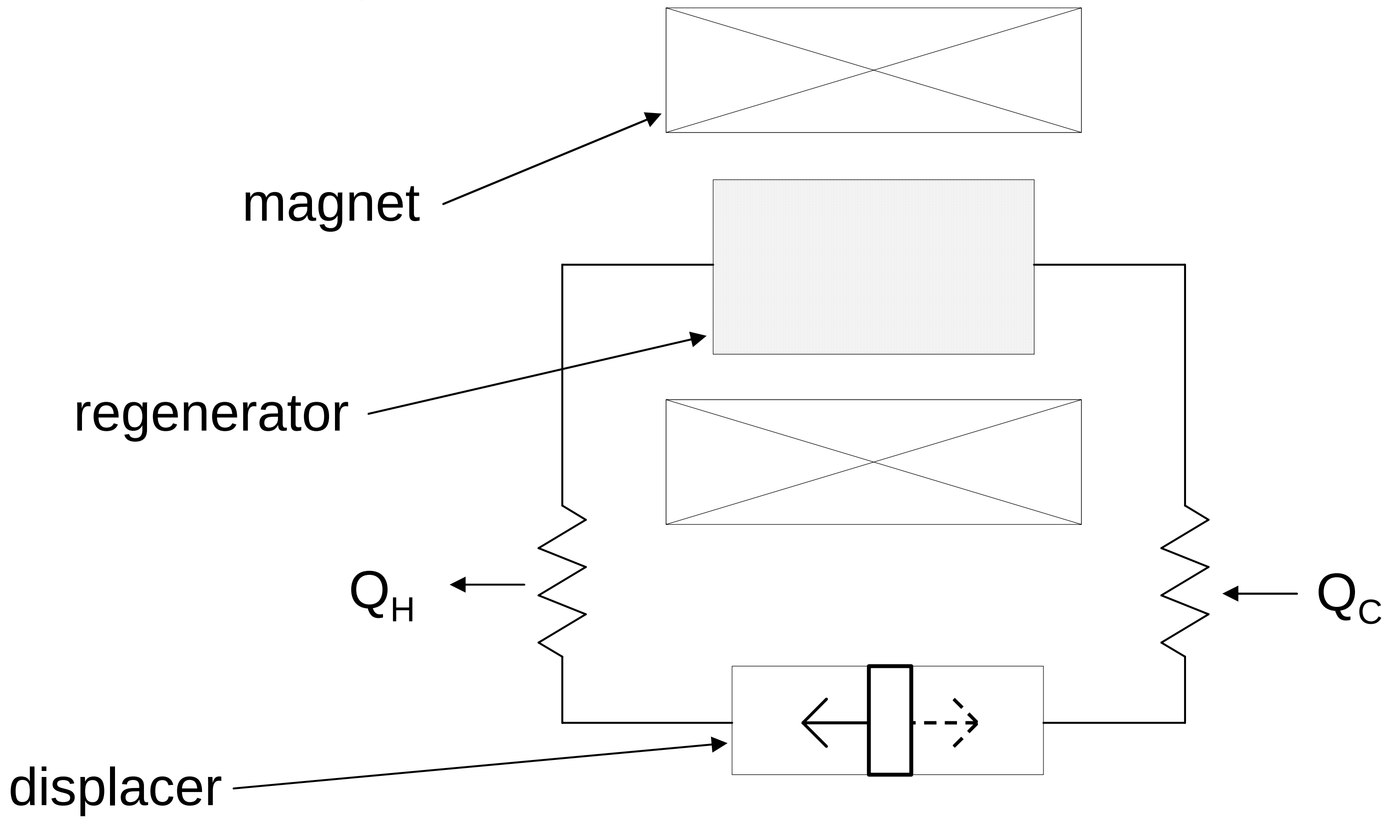


Magnetic Refrigerator Design Considerations

- System configuration
  - rotary, reciprocating, etc.
- Magnetocaloric material selection
- Regenerator design
- Magnetic field
- Heat transfer fluid selection

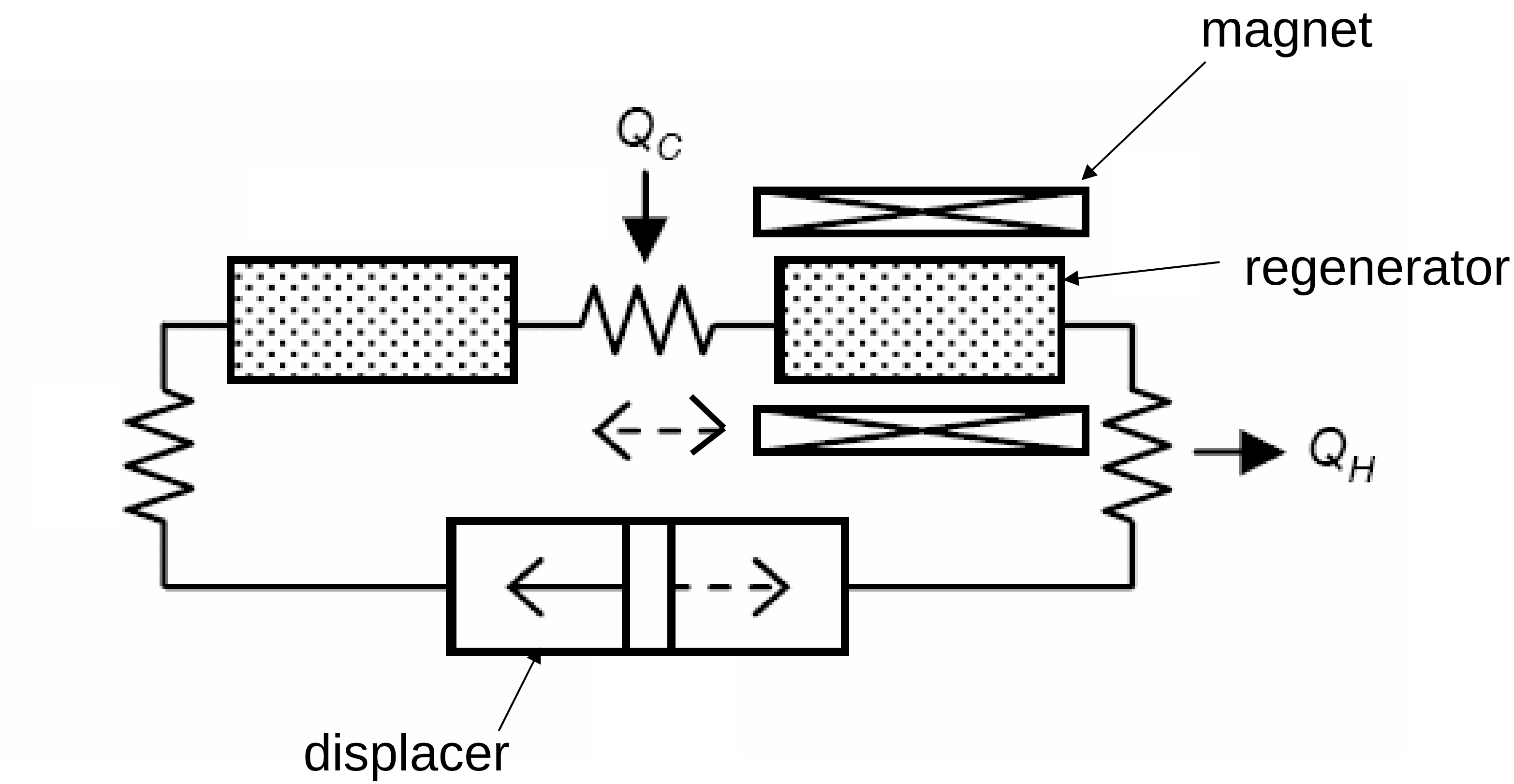
AMRR System Configurations

- Stationary bed with an electromagnet
  - magnetic field is controlled by varying the current to the electromagnet



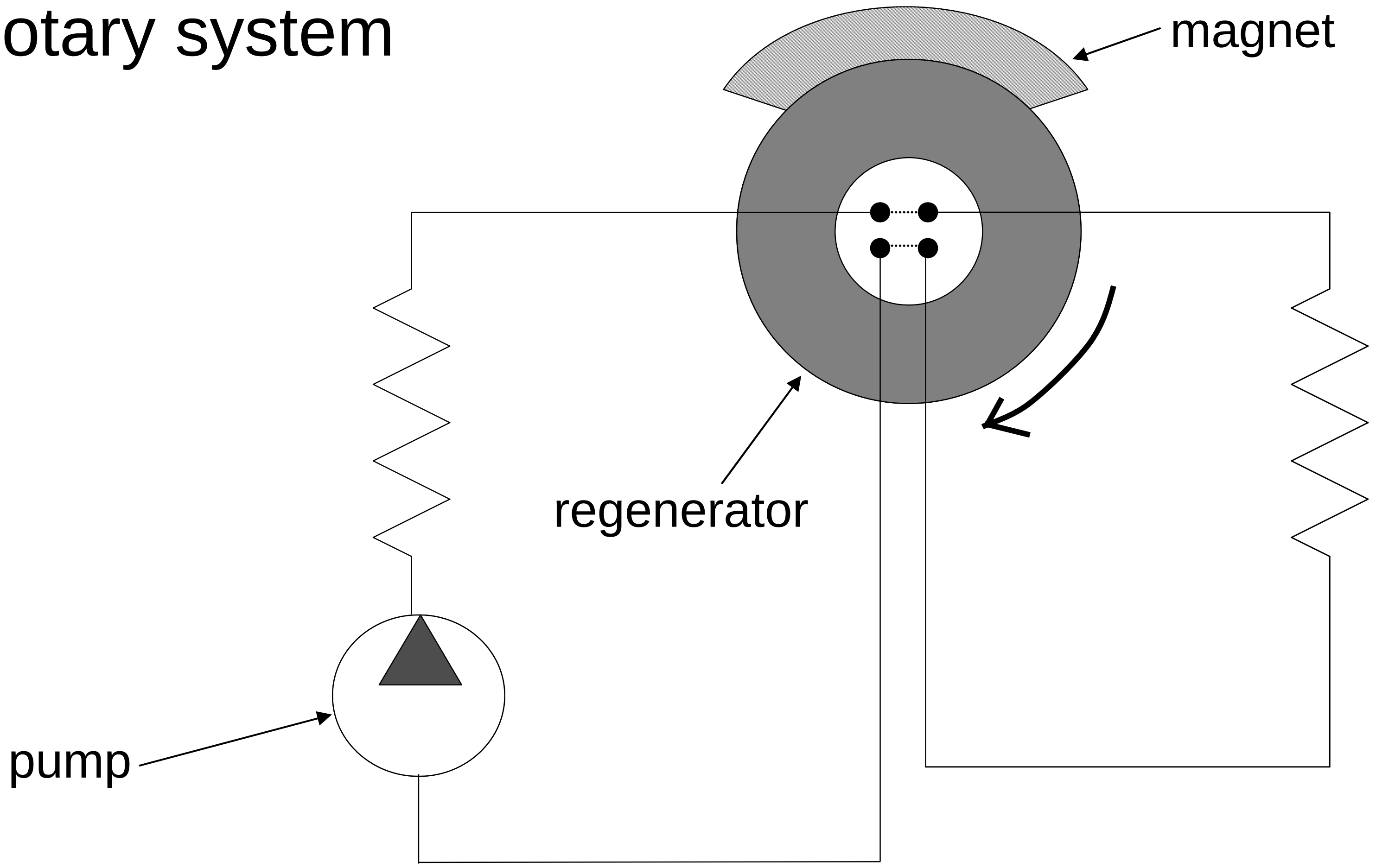
AMRR System Configurations

- Reciprocating system

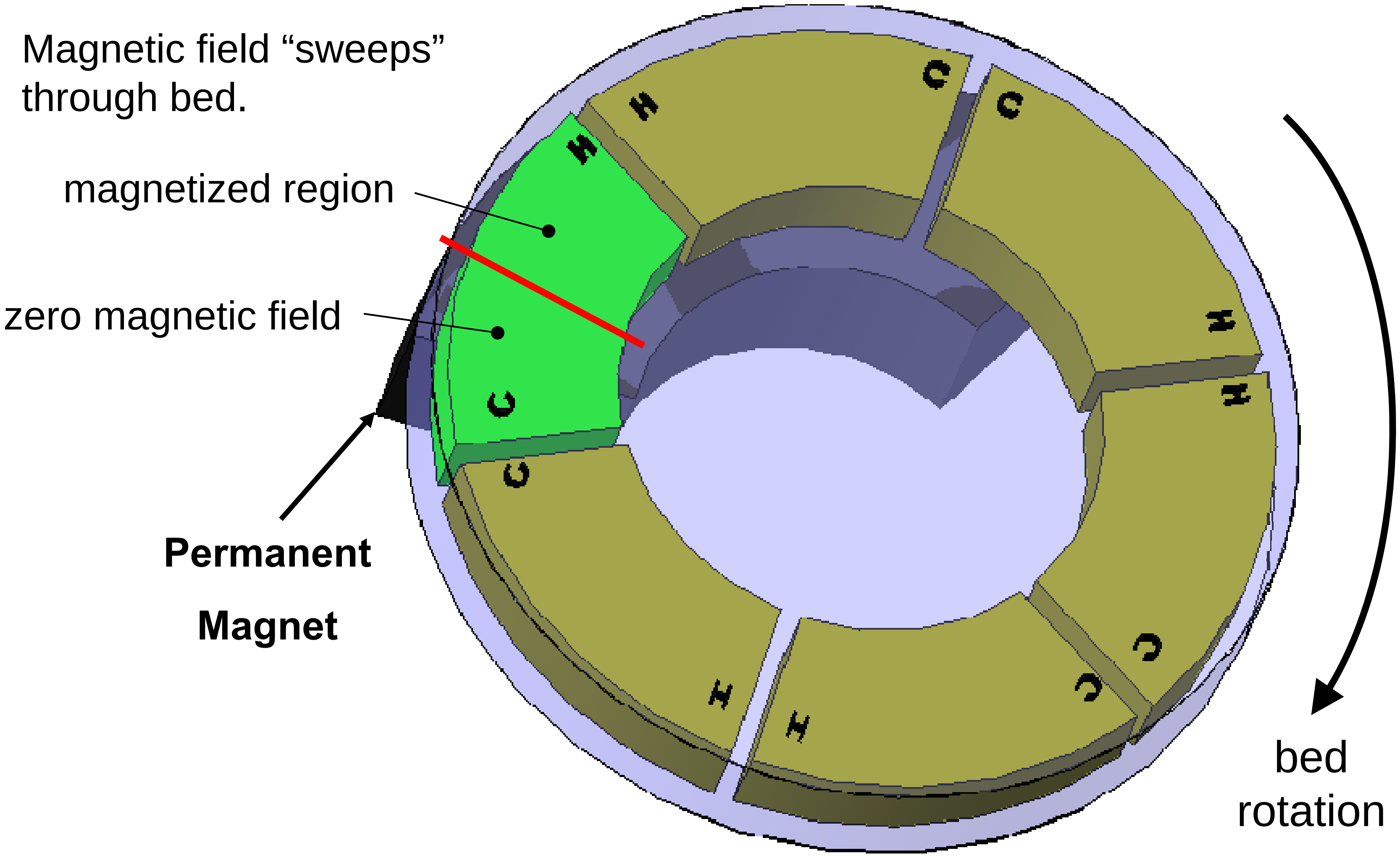


AMRR System Configurations

- Rotary system



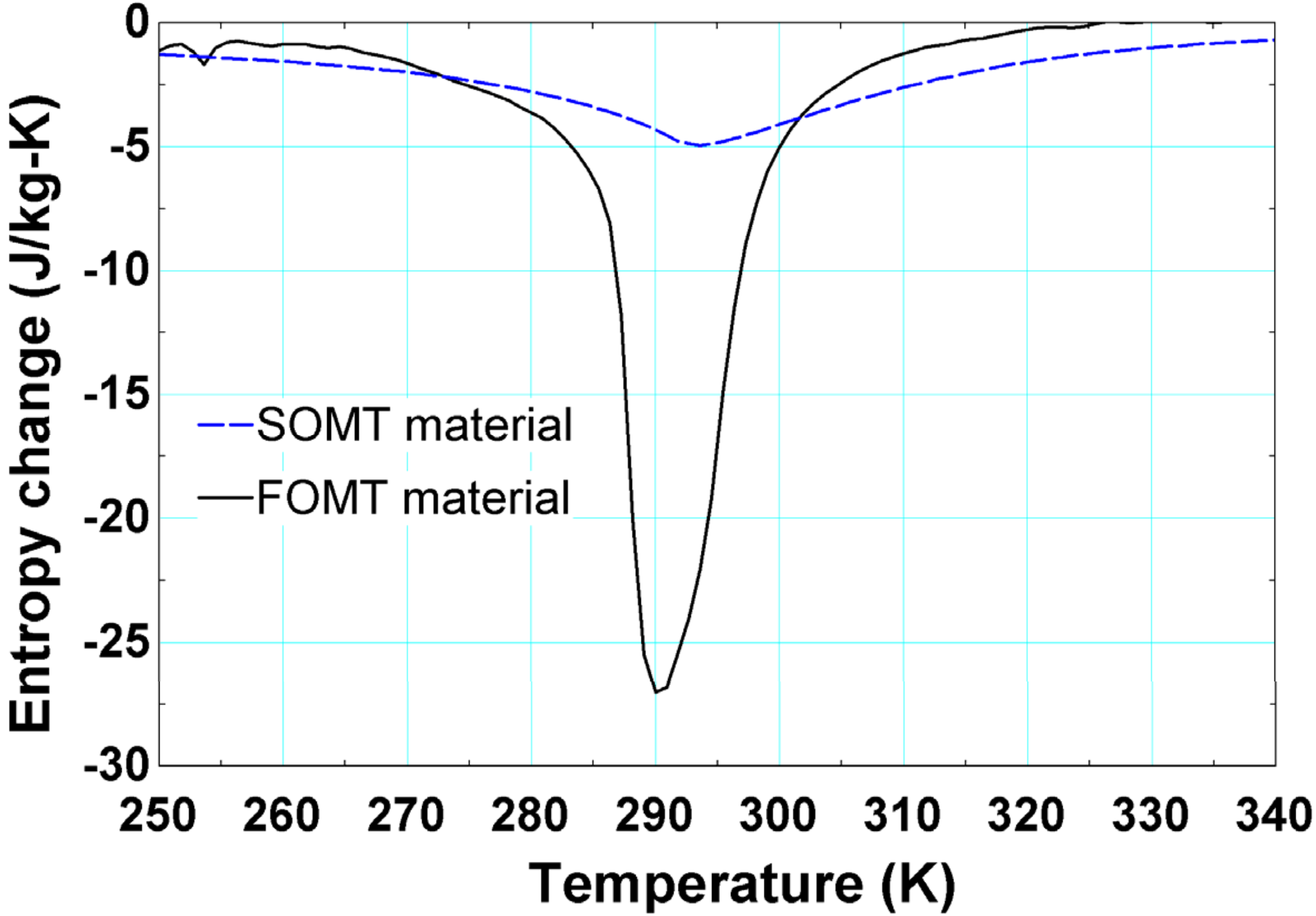
Magnetization in a Rotary Bed



Choosing Magnetocaloric Materials

- Adiabatic temperature change
- Isothermal entropy change
- Thermal conductivity
- Magnetic hysteresis
- Practical issues – cost, corrosion, toxicity, manufacturability

Magnetocaloric Material Properties



Summary of Magnetocaloric Material Properties

Material	T_{Curie} (K)	Type	$-\Delta s_M$ (J/kg-K)	ΔT_{ad} (K)	Hysteresis (K)
Gd	294	SOMT	5.8	5.5	~0
$Gd_5Si_{3.5}Ge_{0.5}$	269	FOMT	27	7	2
$LaFe_{11.7}Si_{1.3}H_{1.1}$	287	FOMT	28	7.1	1
$MnAs_{1-x}Sb_x$					
x=0	318	FOMT	32	5	6
x=0.1	287	FOMT	30	3 (0-1.45 Tesla)	1

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

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

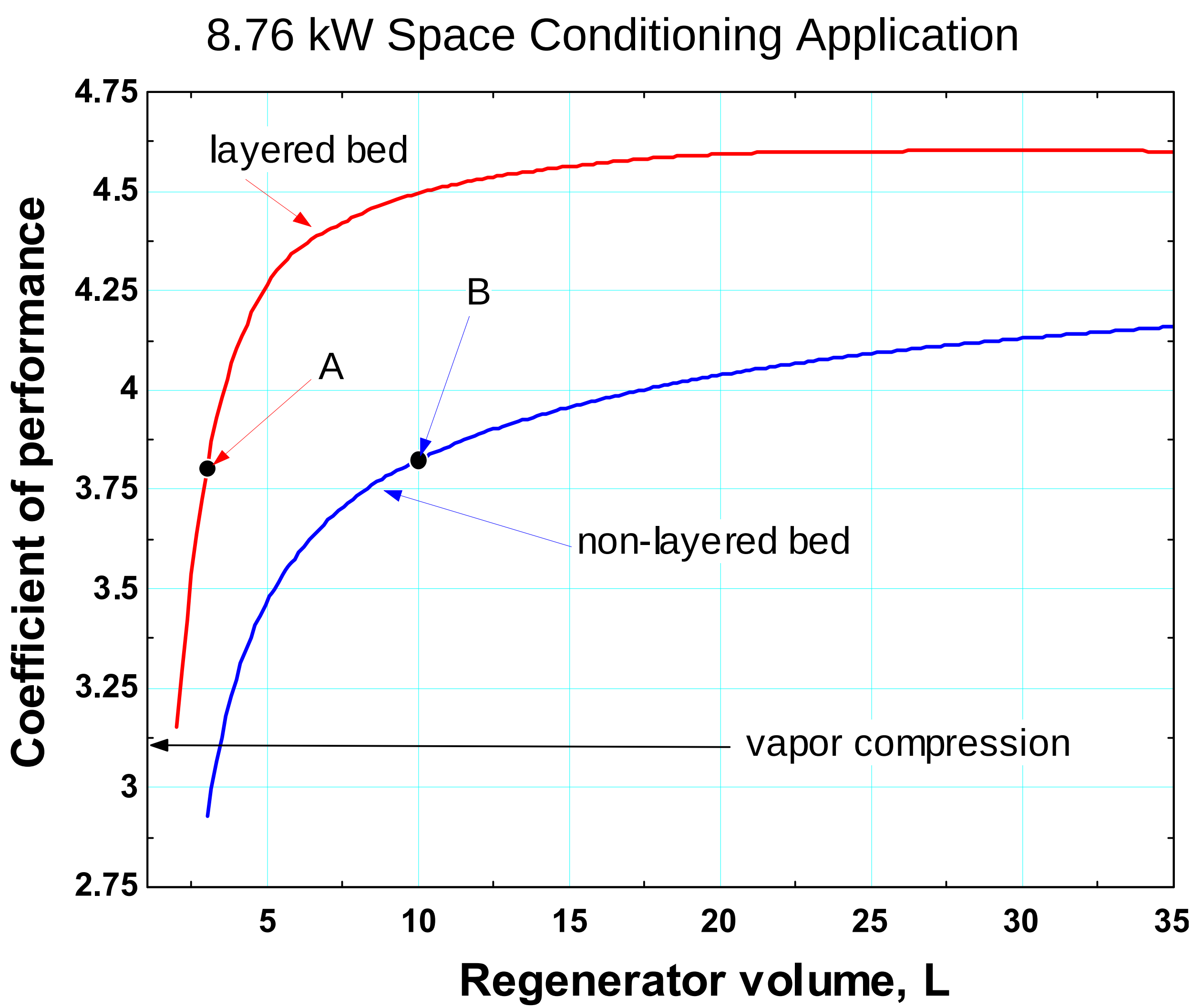
Prototype AMRR Performance Summary

System	$\mu_o H_{Max}$	V_{regen}	Regen material	QC	dT	Regen type
	Tesla	cm^3		W	K	
University of Victoria (2006)	2 (S)	74	Gd, GdTb & GdEr	0	50	crushed part. (0.4mm)
	2 (S)	49	Gd	0	20	spheres (0.2mm)
(2004)	2 (S)	25	Gd	7	4	
Chubu Electri / Tokyo University	4 (S)	484	Gd	100	26	spheres (0.3 mm)
	2 (S)			40	24	
Astronautics	5 (S)	~600	Gd	100	38	spheres (0.15-0.3mm)
				600	0	
	1.5 (P)	33	Gd	15	14	spheres (0.43-0.5mm)
			Gd & GdEr	27	14	spheres (0.25-0.355mm)
			Gd & GdEr	0	25	spheres (0.25-0.355mm)
Nanjing University	1.4 (P)	~200	Gd	0	23	spheres (0.2mm)
			$Gd_5Si_2Ge_2$	0	10	
			GdSiGeGa	40	5	

Promising AMRR Innovations

- High performance magnetocaloric materials with tunable Curie Temperatures
- Layered regenerators
- Rotary systems

Efficiency Dependence on Regenerator Volume – Packed Sphere Regenerator



Practical AMRR Concerns

- High fluid mass flow
  - pressure lower than vapor compression systems
- System size
- Materials processing
- Material oxidation
- Cost

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

Magnetic Refrigeration Research at Risø DTU

Partnership between: Danfoss, Sintex, DTU

Duration: 4 years

Ending date: 31.12.2010

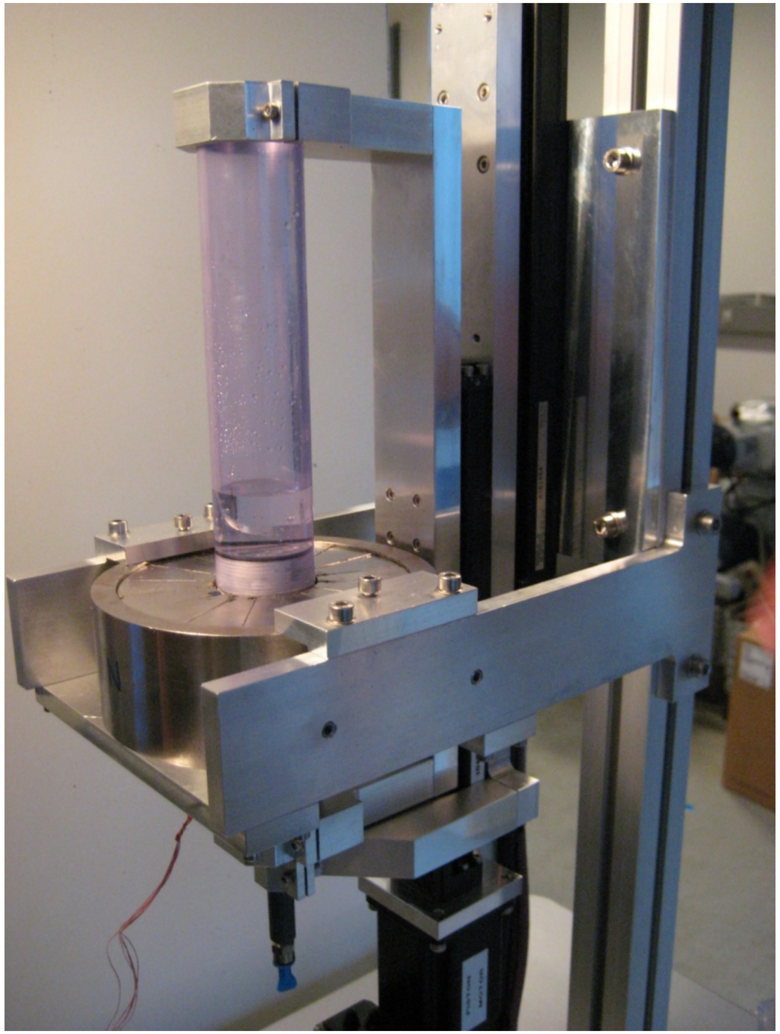
Funding: 20 Mkr

5 Ph.D. students, 3 Postdocs

Challenges
Demonstrate cost-effective systems at commercially relevant temperature spans with high efficiency and environmentally friendly materials

Test Machine at Risø DTU

- Parallel plate regenerator of Gd
  - plate thickness 0,9mm
- Maximum magnetic field ~1.1 Tesla
- Uses a permanent magnet
- Temperature span of 9 K
- Operational since Nov 2007



Future Work at Risø

- Currently designing next generation prototype AMRR
- Project goal: 100W cooling at 40K temperature span
- System should be practical and cost effective
- Prototype will be built in 2009

Conclusions

- Improvements have been made to prototype AMRR systems recently, but the technology is still not mature
- Systems using a layered regenerator beds have been shown higher performance over a relatively large temperature span
- New magnetocaloric materials have potential to significantly improve AMRR performance
  - Gd remains

Modeling Efforts

- Developed a 1D AMRR model
  - used model to determine limits of AMRR technology and investigate control techniques

  K. L. Engelbrecht, G. F. Nellis, and S. A. Klein, 2006, Predicting the Performance of an Active Magnetic Regenerator Refrigerator used for Space Cooling and Refrigeration, *HVAC&R Journal* 12(4):1077-1095

  K. L. Engelbrecht, G. F. Nellis, and S. A. Klein, 2006, Modeling the Transient Behavior of an Active Magnetic Regenerative Refrigerator, *Proceedings of the 11th International Refrigeration and Air Conditioning Conference at Purdue*, West Lafayette, IN

- Used the model to predict the performance of a rotary AMRR prototype

Model Verification – Rotary Input Data

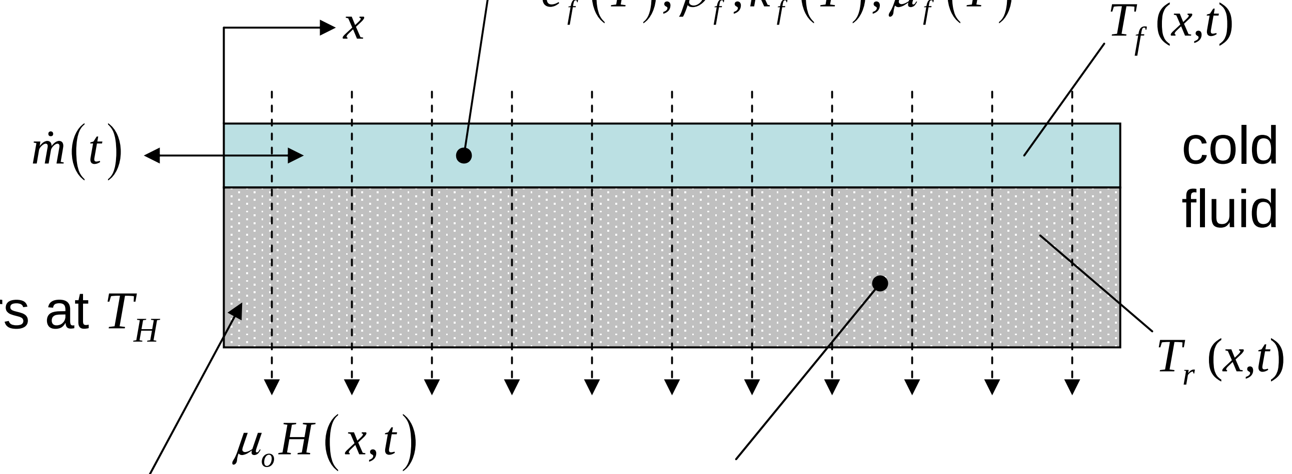
Modeling parameters - geometry

Parameter	Value	Parameter	Value
regenerator type	packed sphere	maximum applied field	1.5 Tesla
regenerator material	Gd	sphere size for packing	0.425-0.5 mm
regenerator beds	6	porosity	0.362
regenerator height	6.6 mm	motor efficiency	N/S
regenerator width	15.9 mm	dwell ratio	1/3
regenerator length	2.025 in	magnet arc	120°
regenerator volume	33 cm^3	heat transfer fluid	90% water/10% ethylene glycol

Uncertainty in Model Inputs

heat transfer fluid properties:

$$c_f(T), \rho_f, k_f(T), \mu_f(T)$$



cold end,
fluid enters at T_C

hot end,
fluid enters at T_H

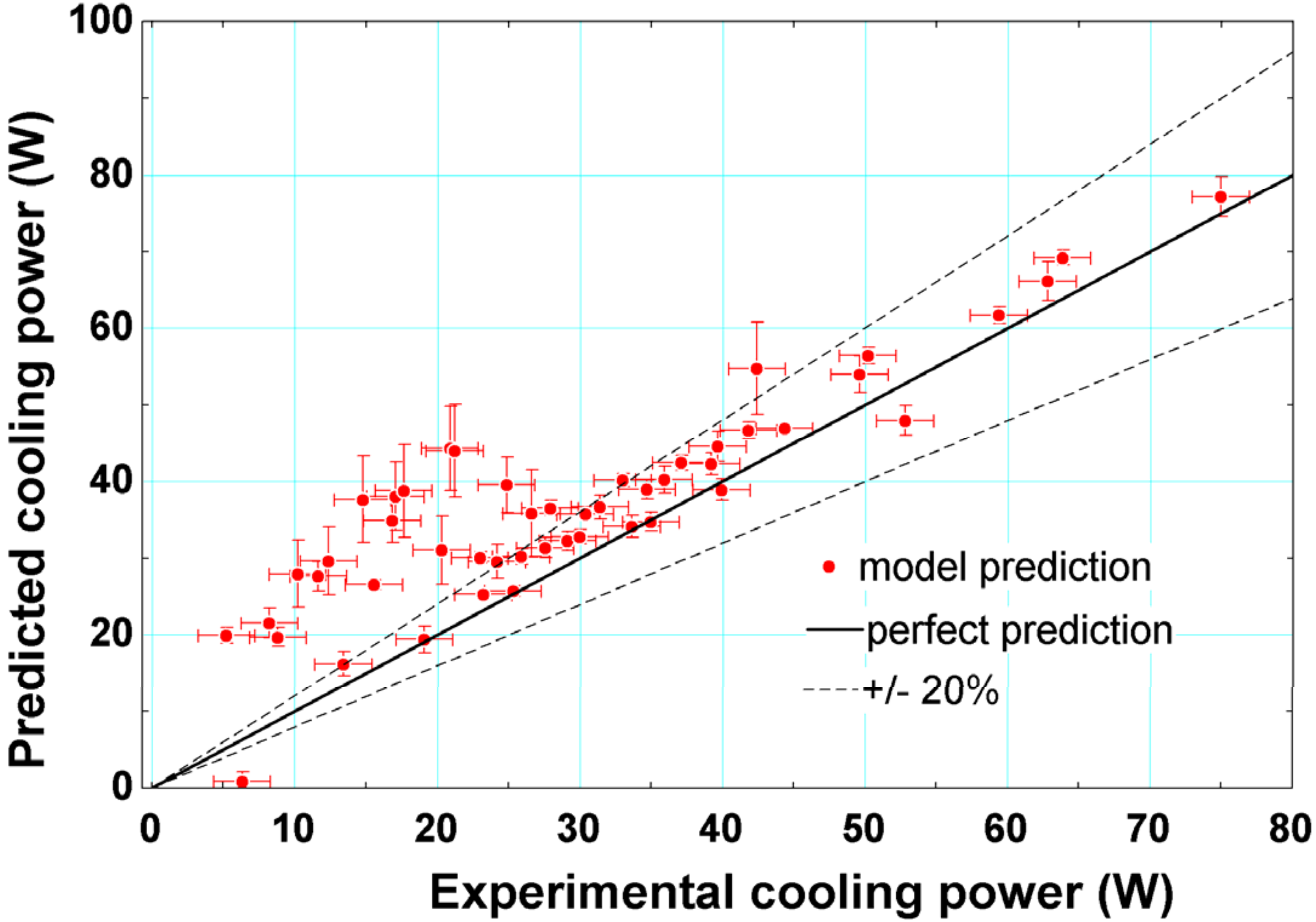
magnetic regenerator material properties:

$$k_r(T,x), \left(\frac{\partial s_r}{\partial \mu_o H}\right)_T (T,x,\mu_o H), c_r(T,x,\mu_o H), \rho_r(x)$$

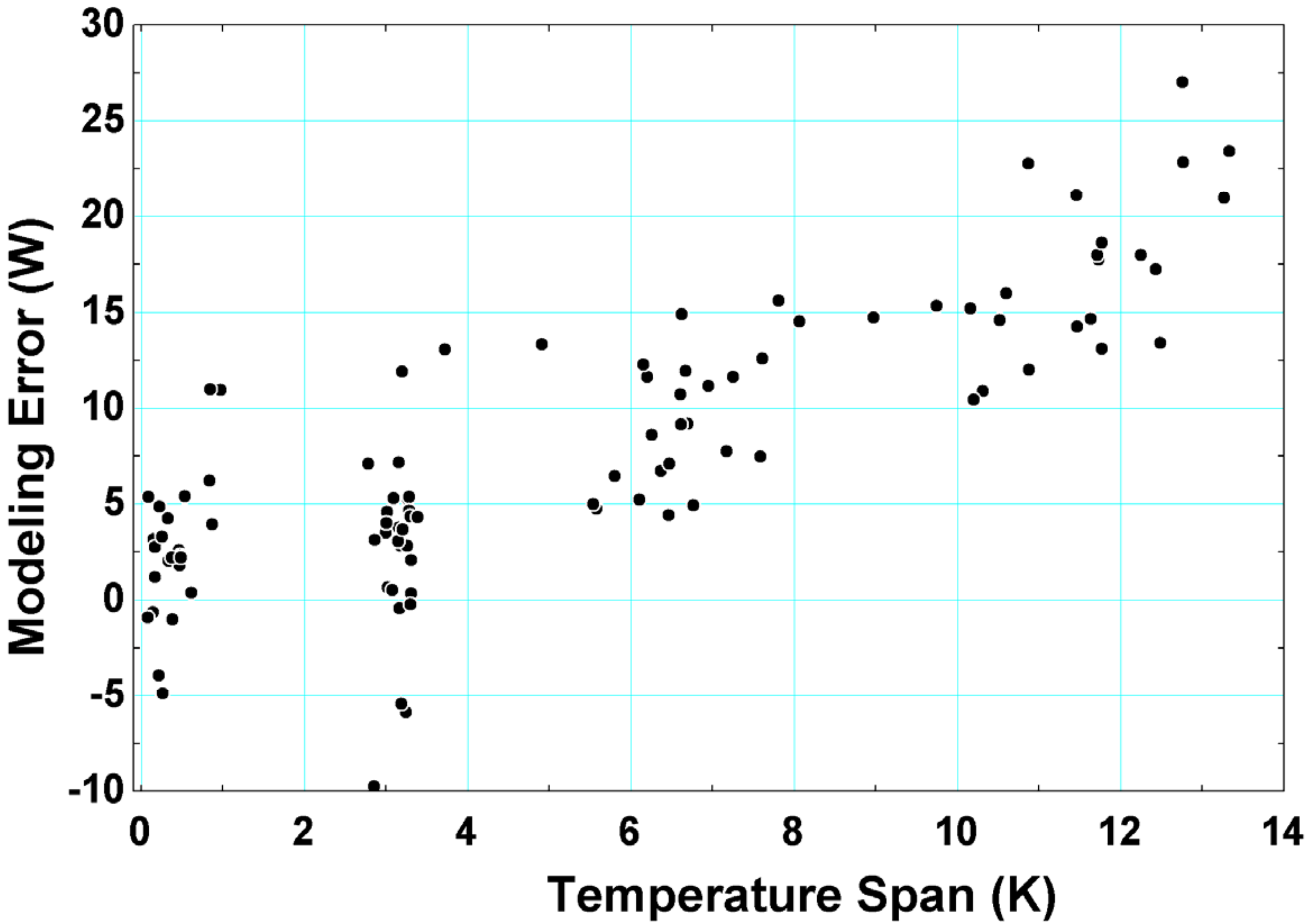
regenerator bed configuration

A_c, L, a_s, d_h, ε, $Nu(Re, Pr)$, $f(Re)$, $k_{eff}(Re, Pr,..)$

Model Results for New Nusselt Number and Reduced Magnetic Field



Modeling Error vs. Temperature Span

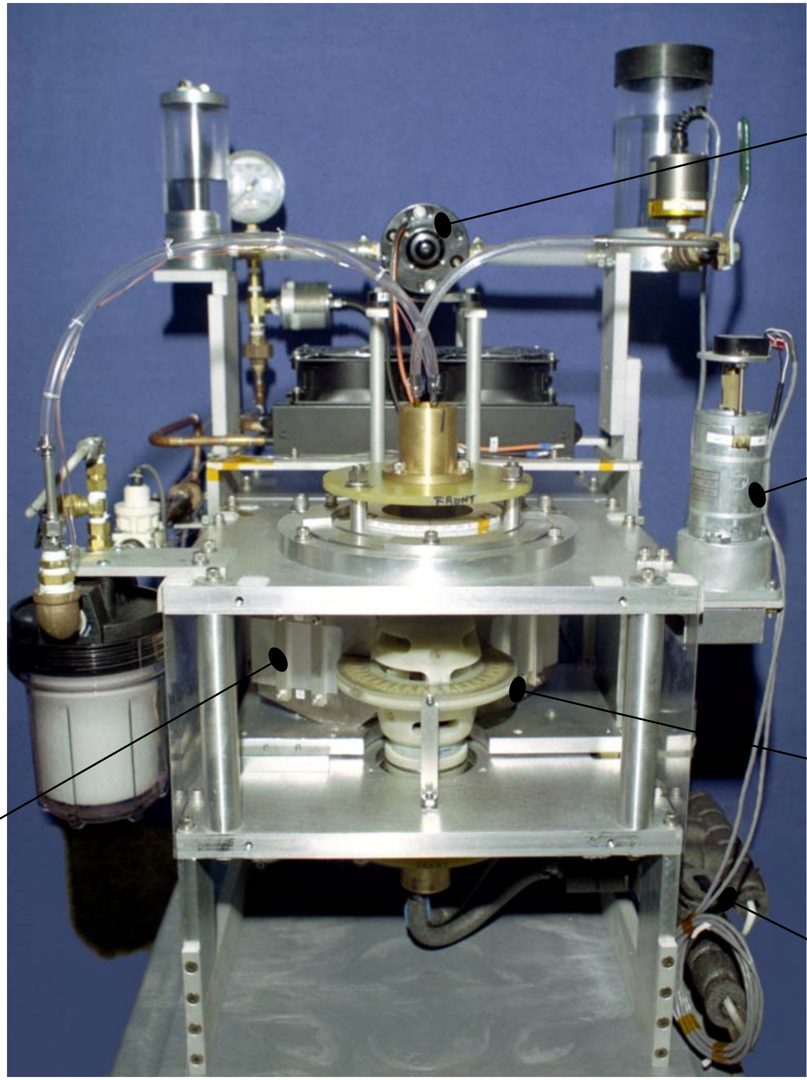


Important AMRR Design/Modeling Considerations

- Effective magnetic field in the regenerator material is different than the field in the gap of the magnet
  – suggests that the permeability of prospective magnetocaloric materials should be considered along with other properties

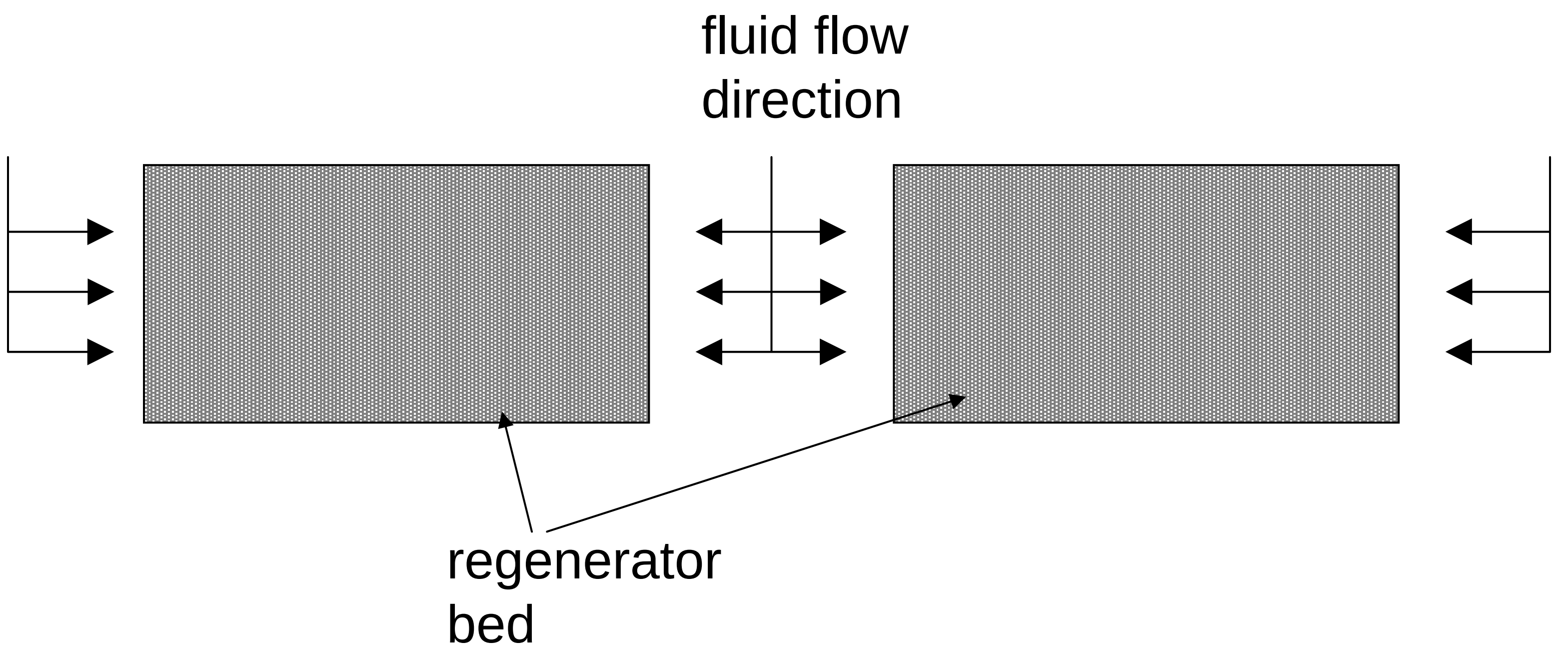
- Heat transfer in the regenerator
  – model agreement improved using a Nu correlation developed for a liquid rather than primarily for a gas

Example of a Prototype Rotary AMRR



Regenerator Flow Unbalance

- for some flow configurations, it is possible that flow through each regenerator may be dependent on flow direction

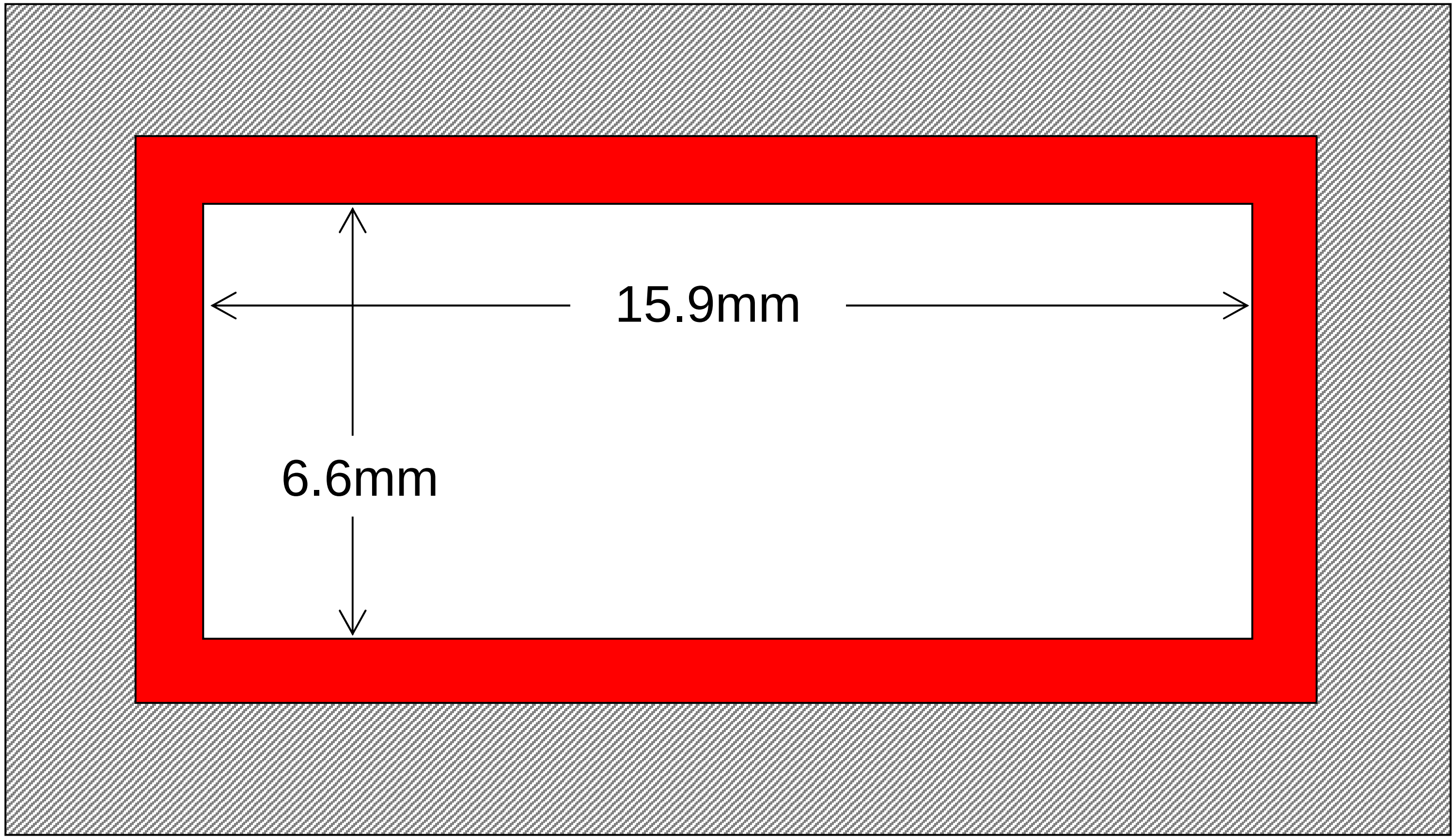


Model Sensitivity to Flow Unbalance

Case	ΔT	Cycle Frequency	Fluid Flow Rate	No Unbalance	5% Unbalance	Cooling Power Loss
	K	Hz	Liter/min	W	W	W
1	0.2	1	0.34	35.72	34.66	1.06
2	0.3	1	0.67	53.20	51.26	1.94
3	0.8	4	0.35	35.38	34.73	0.65
4	0.2	4	0.81	67.80	67.66	0.14
5	13.1	1	0.35	24.61	21.49	3.12
6	11.5	1	0.67	44.09	38.04	6.05
7	11.8	4	0.34	22.36	20.93	1.43
8	17.4	4	0.67	39.13	33.77	5.36

Thermal Properties of the Regenerator Housing

- The regenerator housing is made of G-10, k ~ 0.8 W/m-K, α ~ *4e-7*



Reduced Magnetic Field in the Regenerator

- in a magnetically permeable object, the magnetic field will be less than the magnetic field in free space
  - actual magnetic field depends on the shape of the material and the permeability as a function of magnetic field

- For a sphere of constant permeability in a uniform magnetic field the magnetic field in the material is

$$\mu_0 H_{eff} = \mu_0 H^0 \frac{3}{2 + \frac{\mu}{\mu_0}}$$

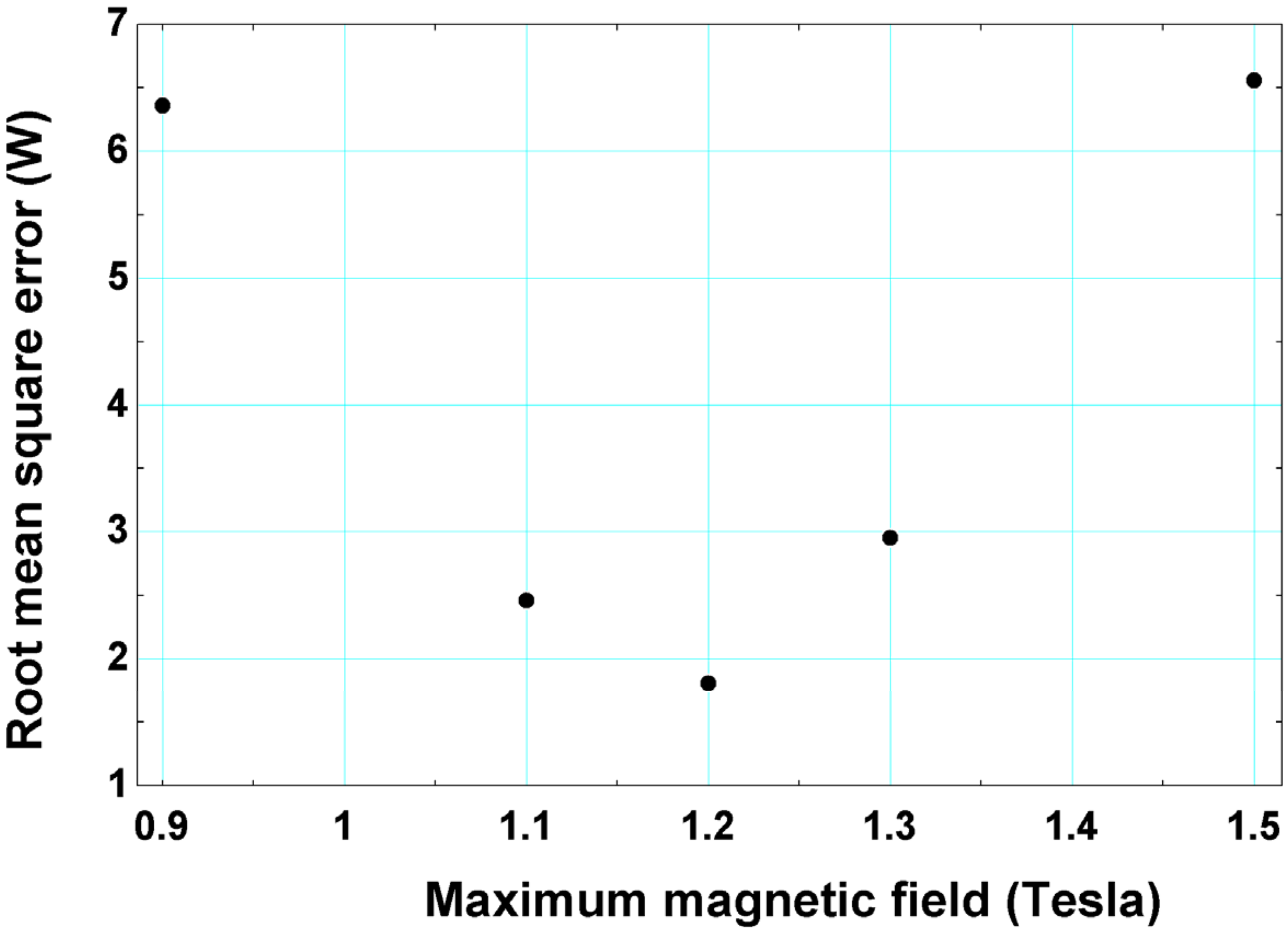
permeability of regenerator material (→ μ)

- It is important to determine the actual effective magnetic field in the regenerator

Reduction in Cooling Power at Reduced Heat Transfer

Case	ΔT	Cycle Frequency	Fluid Flow Rate	Predicted Cooling Power	Cooling Power Loss
	K	Hz	Liter/min	W	
1	0.2	1.0	0.34	35.7	1.0%
2	0.3	1.0	0.67	53.2	0.3%
3	0.8	4.0	0.35	35.4	8.3%
4	0.2	4.0	0.81	67.8	2.2%
5	13.1	1.0	0.35	24.6	10.8%
6	11.5	1.0	0.67	44.1	19.6%
7	11.8	4.0	0.34	22.4	17.1%
8	17.4	4.0	0.67	39.1	25.4%

Determining Actual Magnetic Field



Governing Equations

Fluid:

$$\underbrace{\dot{m}(t)c_f(T_f)\frac{\partial}{\partial x}[T_f]}_{\text{enthalpy flow}}+\underbrace{\frac{Nu(Re_f,Pr_f)k_f(T_f)}{d_h}a_s\,A_c(T_f-T_r)}_{\text{heat transfer to regenerator material}}+\underbrace{\rho_f\,c_f(T_f)A_c\,\varepsilon\frac{\partial}{\partial t}[T_f]}_{\text{capacity of entrained fluid}}$$

$$\underbrace{-k_{disp}A_c\frac{\partial^2 T_r}{\partial x^2}}_{\text{axial dispersion}}=\underbrace{\left|\frac{\partial p}{\partial x}\frac{\dot{m}(t)}{\rho_f}\right|}_{\text{viscous dissipation}}$$

Regenerator:

$$\underbrace{\frac{Nu(Re_f,Pr_f)k_f(T_f)}{d_h}a_s\,A_c(T_f-T_r)}_{\text{heat transfer from fluid}}+\underbrace{A_c(1-\varepsilon)\mu_o H\frac{\partial M}{\partial t}}_{\text{magnetic work}}+\underbrace{k_{eff}A_c\frac{\partial^2 T_r}{\partial x^2}}_{\text{axial conduction}}=\underbrace{\rho_r\,A_c(1-\varepsilon)\frac{\partial u_r}{\partial t}}_{\text{energy stored in matrix}}$$

Modeling Efforts

- Developed a 1D AMRR model flexible design tool capable of predicting the performance of an AMRR system

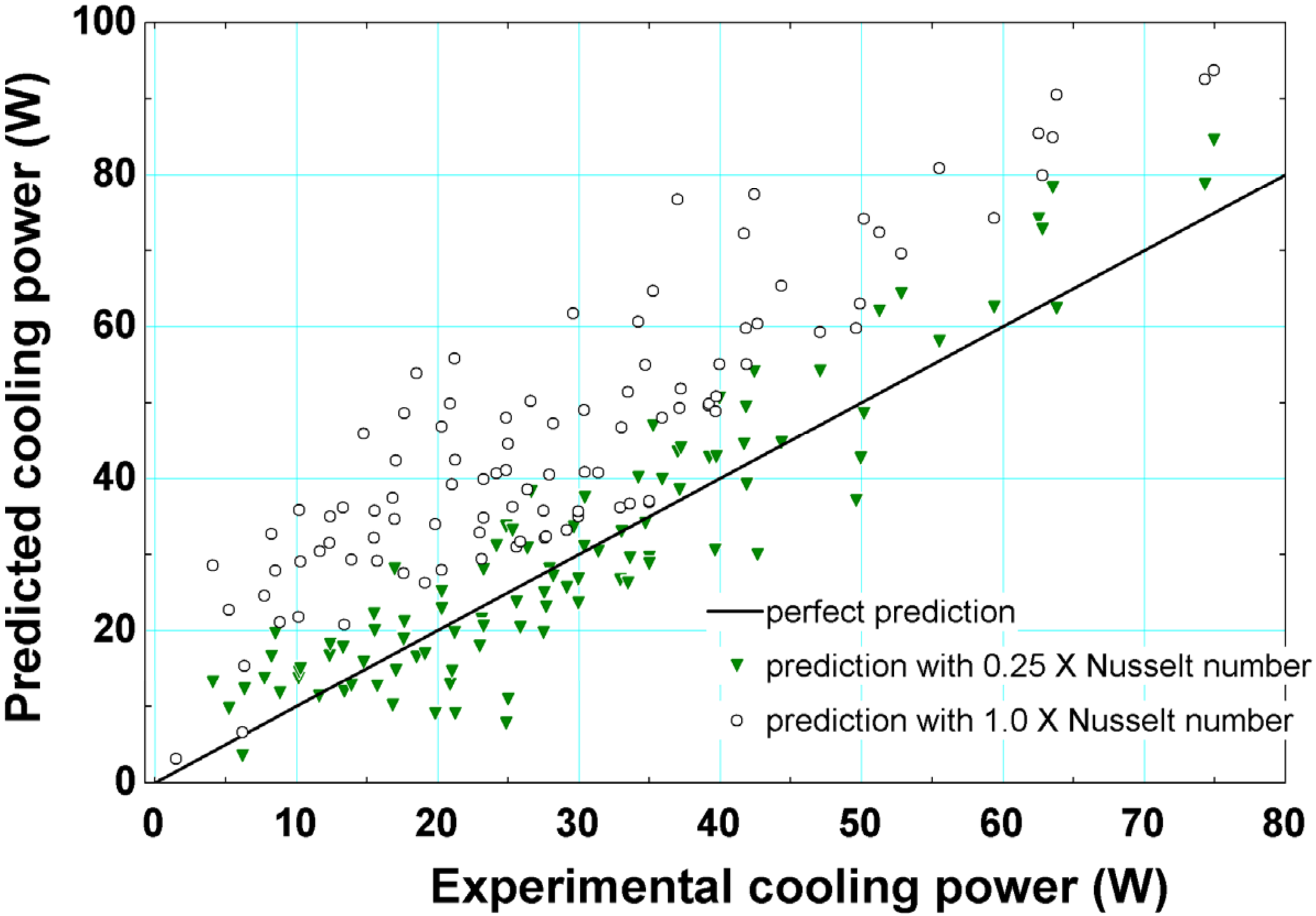
- Verify the model experimentally

- Make the model publicly available

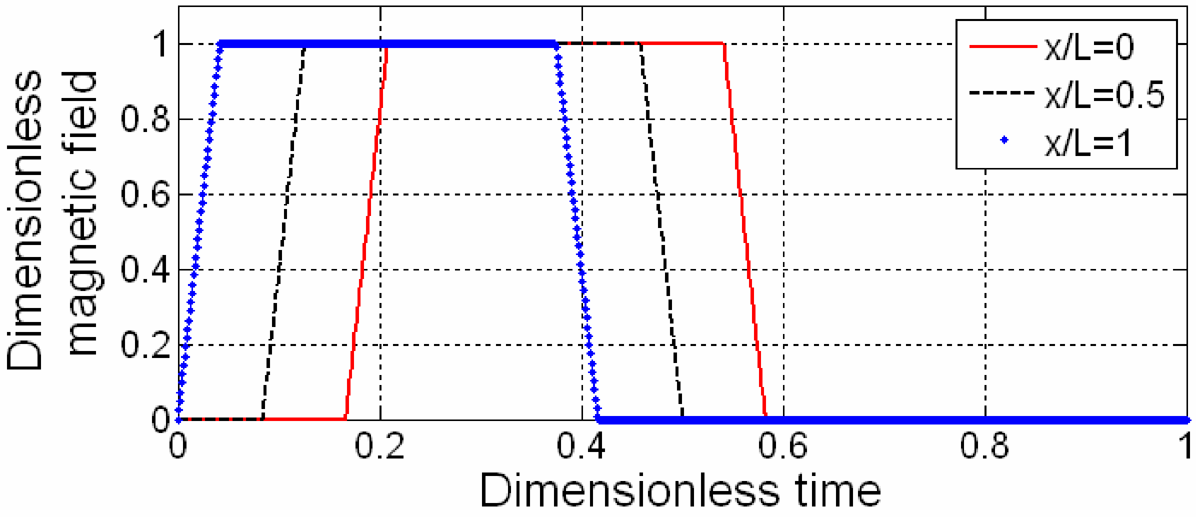
Representative Experimental Cases

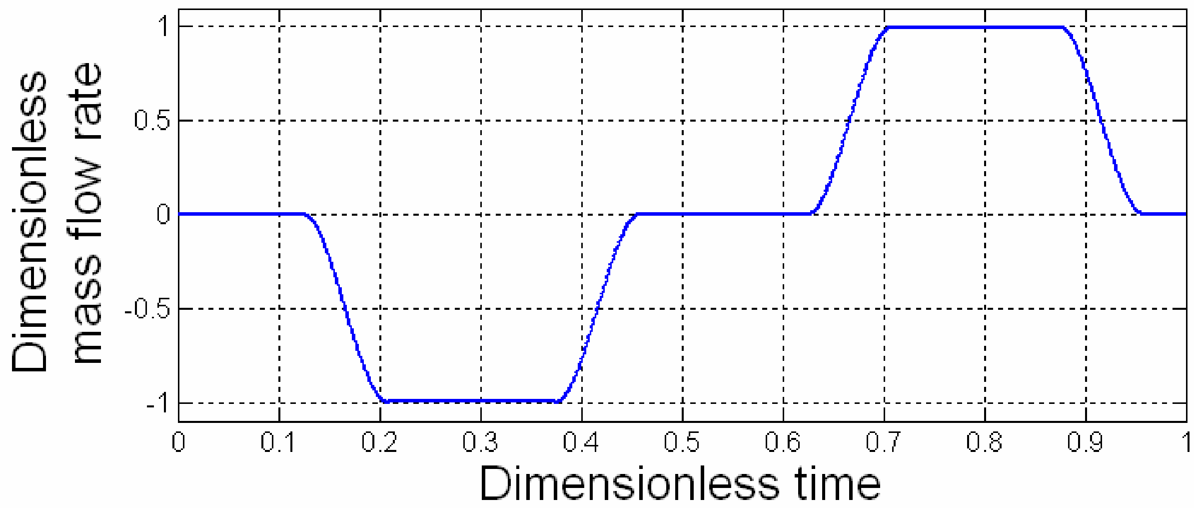
Case	Temperature Span		Cycle Frequency		Fluid Flow Rate	
	low	high	low	high	low	high
1	X		X		X	
2	X		X			X
3	X			X	X	
4	X			X		X
5		X	X		X	
6		X	X			X
7		X		X	X	
8		X		X		X

Model Sensitivity to Heat Transfer Coefficient in the Regenerator

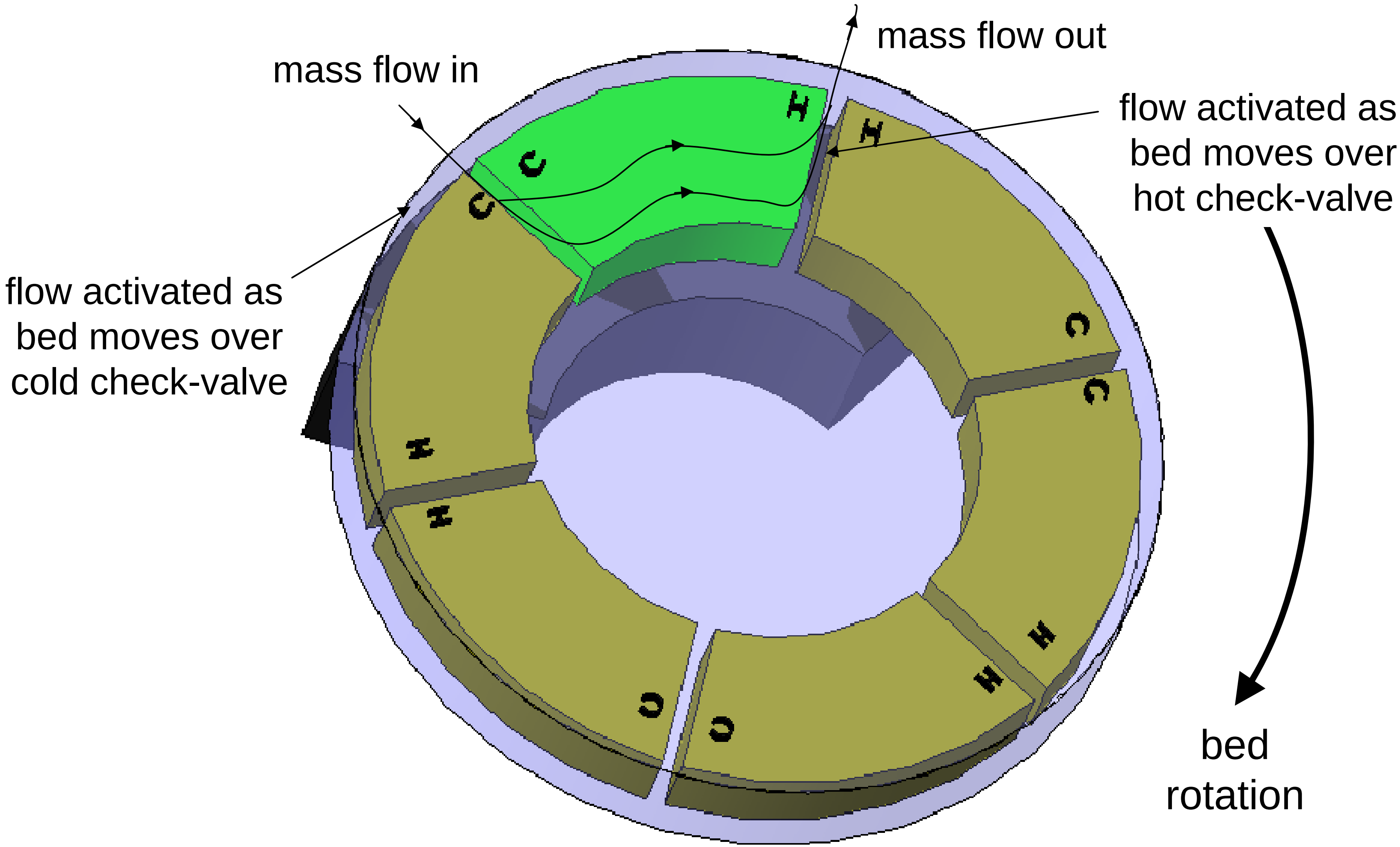


Modeling Experimental Data – Cycle Configuration





Cold to Hot Flow in a Rotary Bed

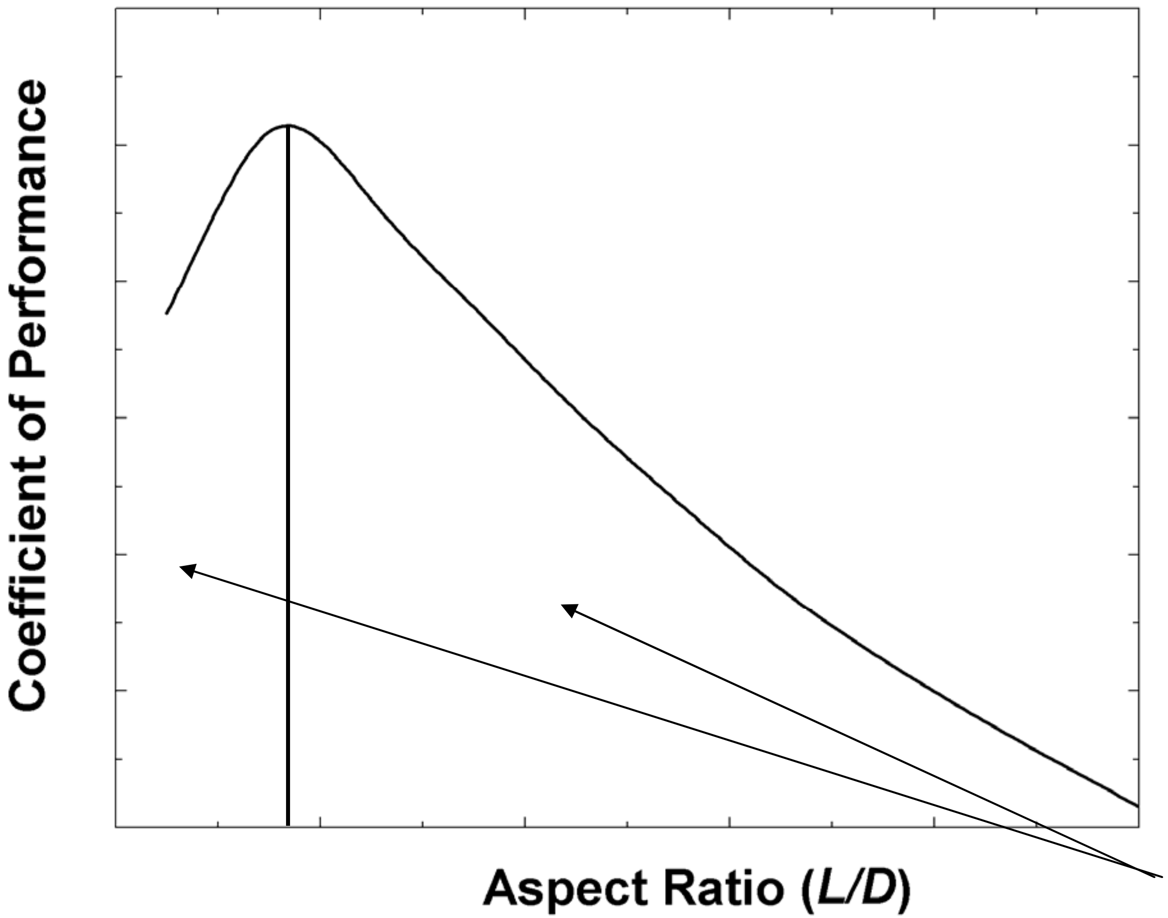


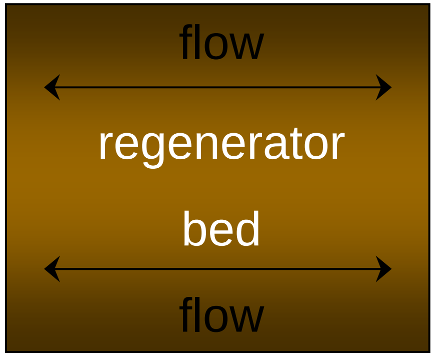
Prototype AMRR Performance

System	**$\mu_o H_{Max}$**	**V_{regen}**	**Regen material**	**QC**	**dT**	**Regen type**
	Tesla	cm3		W	K	
University of	2 (S)	74	Gd, GdTb & GdEr	0	50	crushed part. (0.4mm)
Victoria	2 (S)	49	Gd	0	20	spheres (0.2mm)
	2 (S)	25	Gd	7	4	
Chubu Electric/	4 (S)	484	Gd	100	26	spheres (0.3 mm)
Toshiba	2 (S)			40	24	
Astronautics	5 (S)	~600	Gd	100	38	spheres (0.15-0.3mm)
				600	0	
Astronautics	1.5 (P)	33	Gd	15	14	spheres (0.43-0.5mm)
			Gd & GdEr	27	14	spheres (0.25-0.355mm)
			Gd & GdEr	0	25	spheres (0.25-0.355mm)
Nanjing University	1.4 (P)	~200	Gd	0	23	spheres (0.2mm)
			Gd5Si2Ge2	0	10	
			GdSiGeGa	40	5	

Efficiency Dependence on Aspect Ratio

Volume of magnetic material is held constant while the length and diameter of the regenerator bed are varied





Pump losses begin to dominate as L/d increases

Axial conduction losses begin to dominate as L/d decreases

Numerical Verification: Schumann Solution

- Solid and fluid in a regenerator are initially at a uniform temperature of 0 K and fluid at temperature T_H enters at t=0

- Analytical solution for transient temperature profiles of the fluid and solid exists
  - Shitzer, A. and M. Levy, 1983, Transient Behavior of a Rock-Bed Thermal Storage Sytem Subjected to Varibable Inlet Air Temperatures: Analysis and Experimentation, *Journal of Solar Engineering*, vol 105: p. 200-206

- Solution assumes constant material properties, no axial conduction, and uniform heat transfer between fluid and solid

- The temperature profiles predicted by the numerical model can be verified against this analytical solution

Model Verification – Single Blow