Cascading implementation of a magnetocaloric heat pump for building space heating applications

10th International Conference on System Simulation in Buildings
SSB 2018
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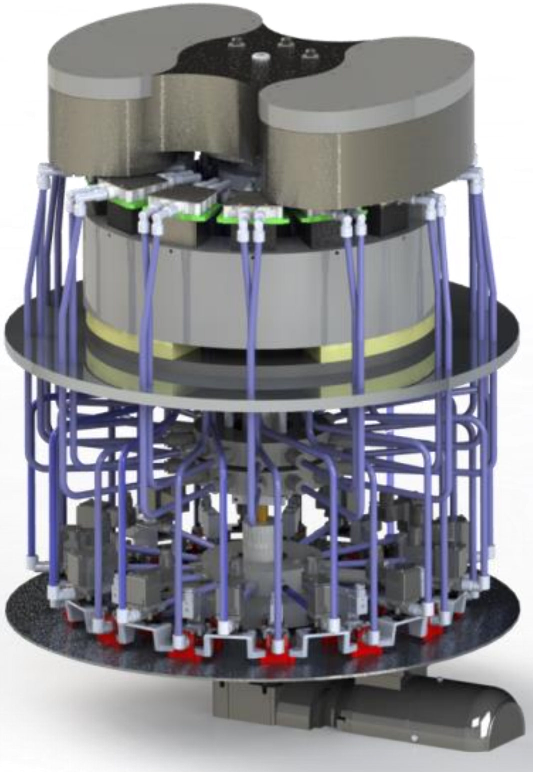

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Department of Civil Engineering

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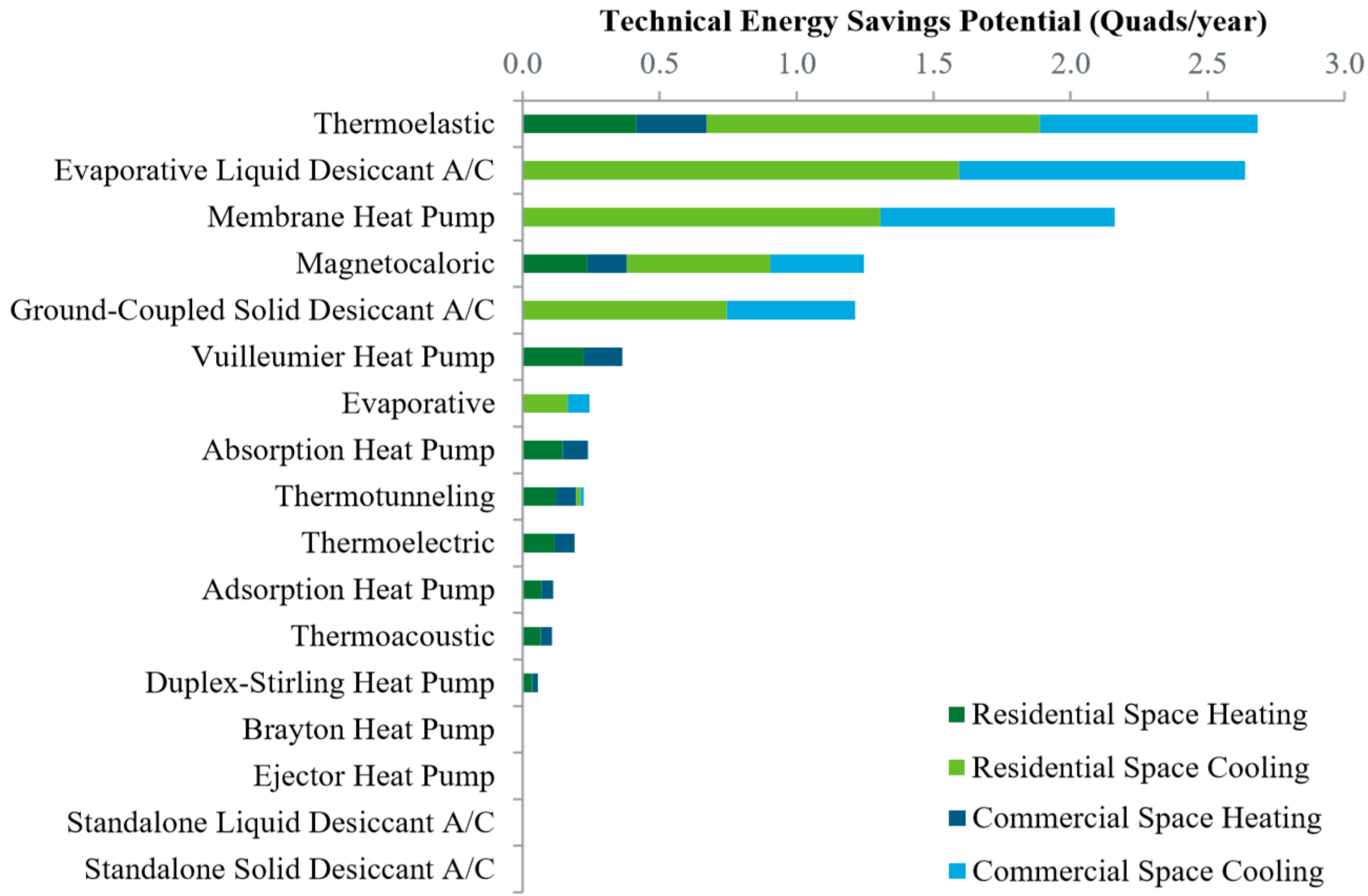
10-12 December 2018

Motivations

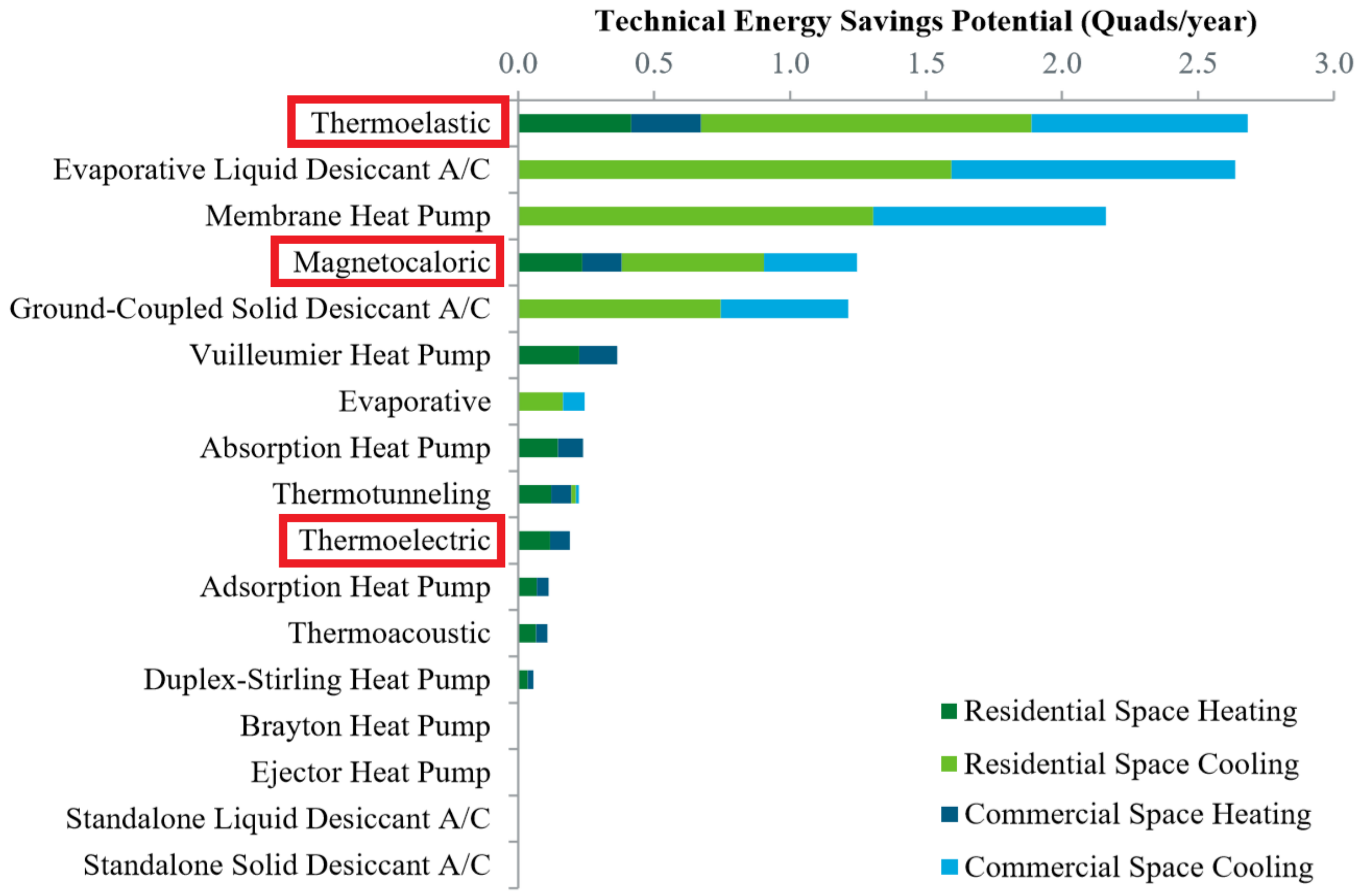
- We need to save the world !!! (obviously)
- Large continuous increase of market demand for heat pumps
- Need to develop new cost effective heating / cooling systems
- Problem with use of liquid / gas refrigerant:
  - F-gas
  - Flammability
  - Toxicity
  - Greenhouse gas effect
  - …

Potential of innovative systems



Comparison of technical energy savings potential [U.S. Department of Energy, 2014]

Potential of innovative systems



Comparison of technical energy savings potential [U.S. Department of Energy, 2014]

Caloric effects

Caloric effect in solid refrigerant: material phase transition resulting in large adiabatic temperature change when specific parameter of surrounding environment is changed:

- **Electrocaloric** effect: variation of electrical field
- **Barocaloric** effect: variation of hydrostatic pressure
- **Elastocaloric** effect: variation of uniaxial mechanical stress
- **Magnetocaloric** effect: variation of magnetic field

Potential of caloric effects

- Large COPs (in theory) because (nearly) reversible caloric effects
- Solid refrigerant + sustainable heat transfer fluid
- Active regenerator cycle to achieve temperature span above adiabatic temperature change of caloric effects

…

- But not mature technologies compared to vapor-compression

Objectives of the ENOVHEAT project

Creation of an innovative and efficient magnetocaloric heat pump for a single family house in Denmark:

- Provide indoor space heating during winter (no DHW)
- 1 - 1.5 kW of heating power
- 20 - 25 K of temperature span between heat source and heat sink
- COP of 5

Magnetocaloric effect

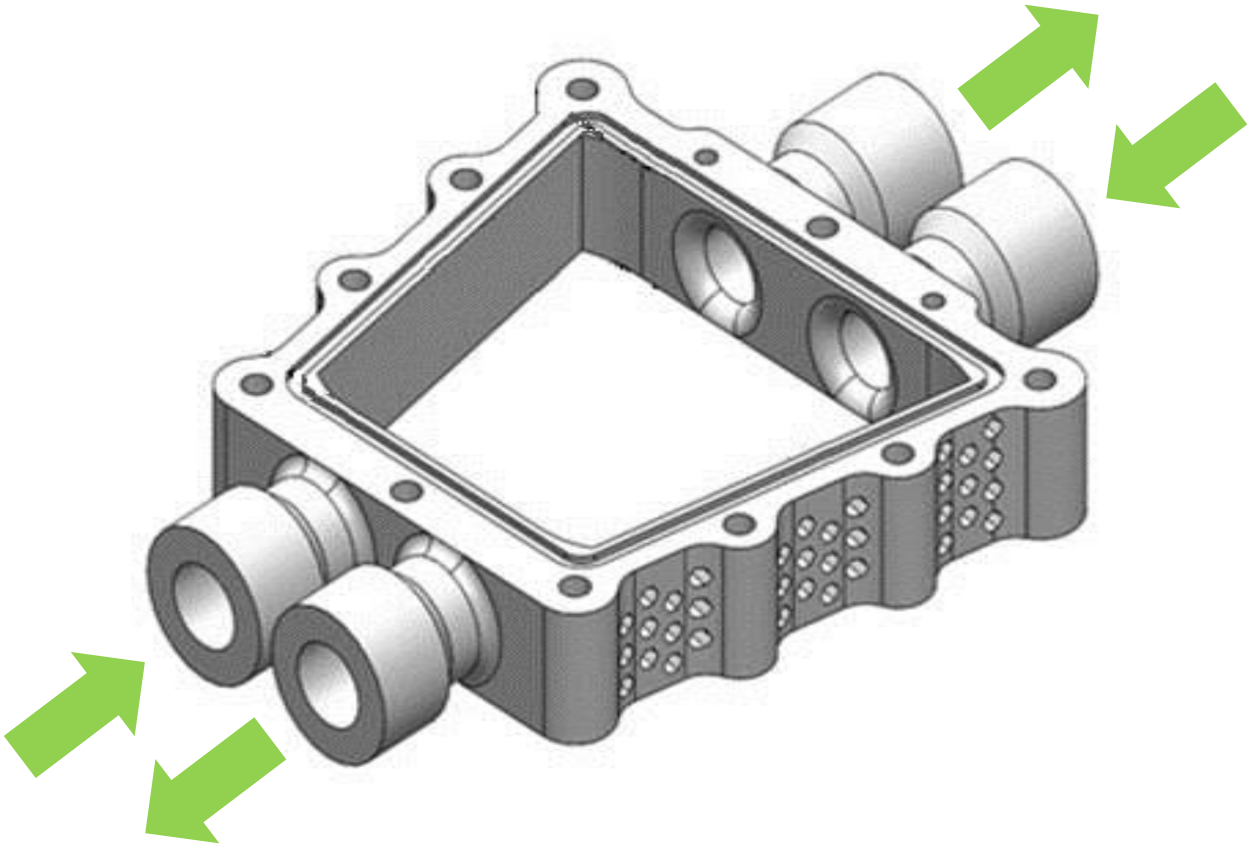
Magnetocaloric technology:

- Currently the most studied and developed of all caloric effects
- Reversible temperature change in a magnetocaloric material when subjected to magnetization or demagnetization:
  - Warms up when magnetic field is applied
  - Cools down when magnetic field is removed
- Can be used to create a thermodynamic cycle (active magnetic regenerator cycle) to transfer heat from cold source to warmer heat sink

Magnetocaloric material

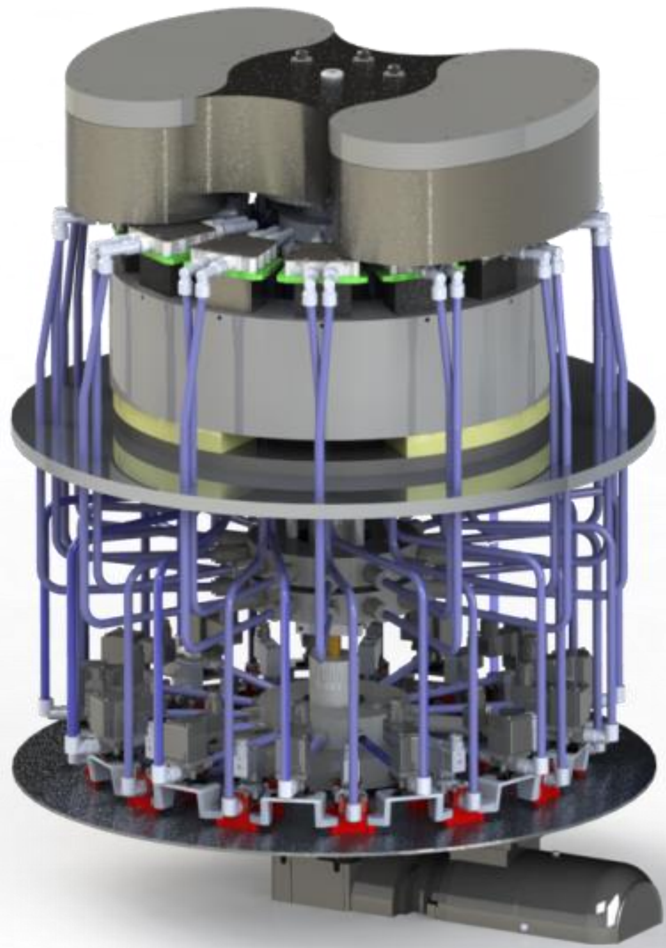
Gadolinium: a famous magnetocaloric material

Magnetocaloric heat pump



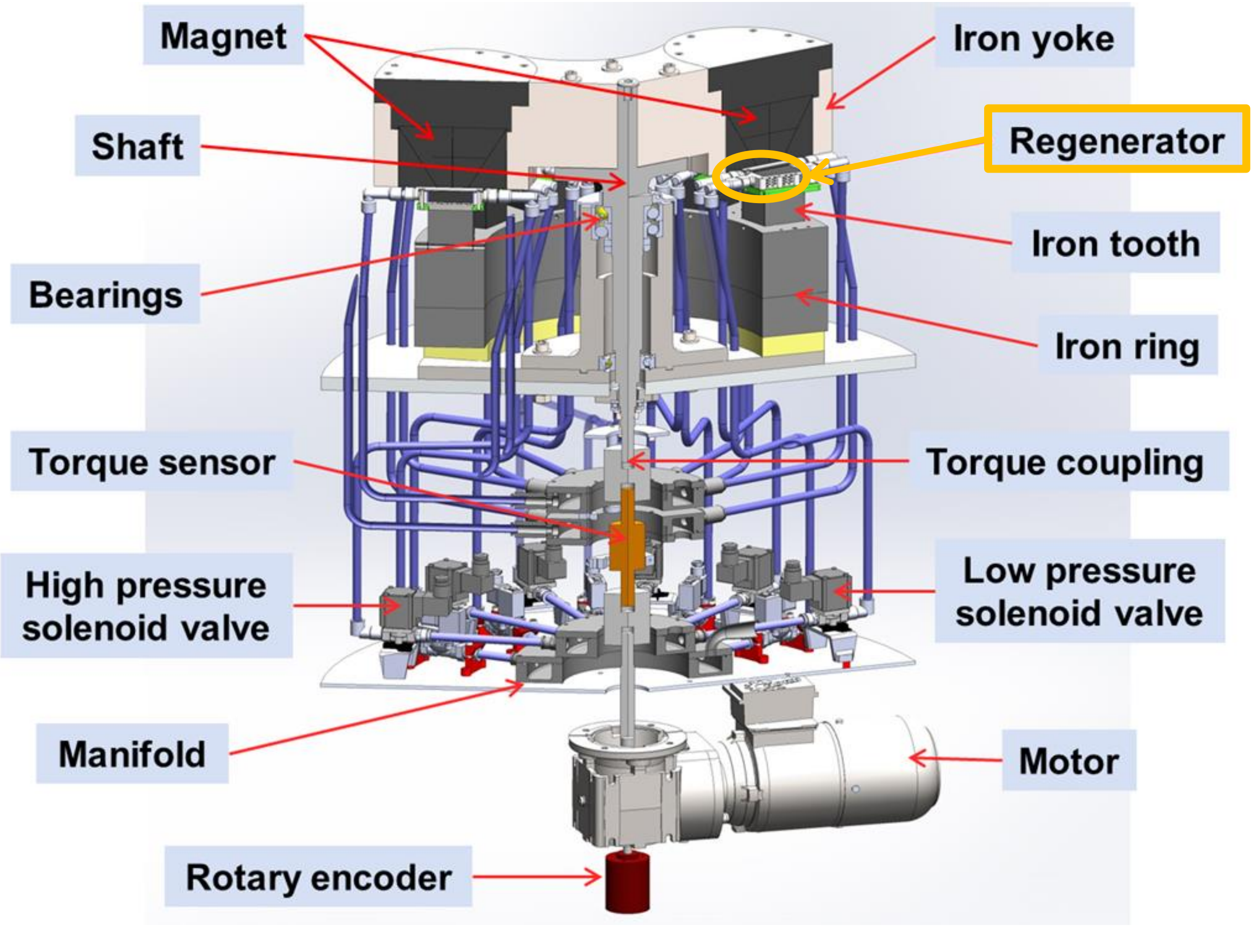
Regenerator casing containing magnetocaloric material (packed sphere bed)

Magnetocaloric heat pump



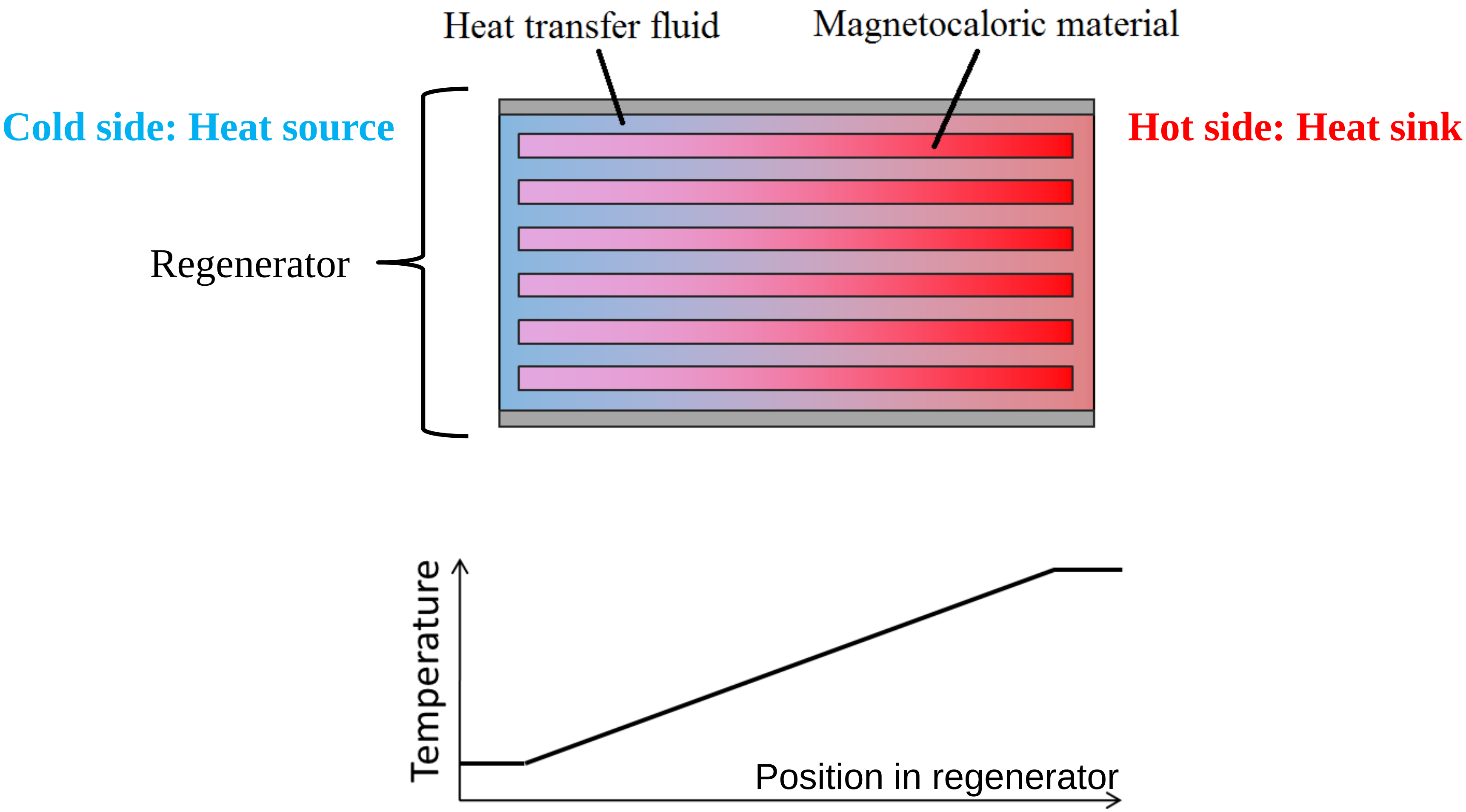
”MagQueen” the ENOVHEAT magnetocaloric heat pump prototype

Magnetocaloric heat pump



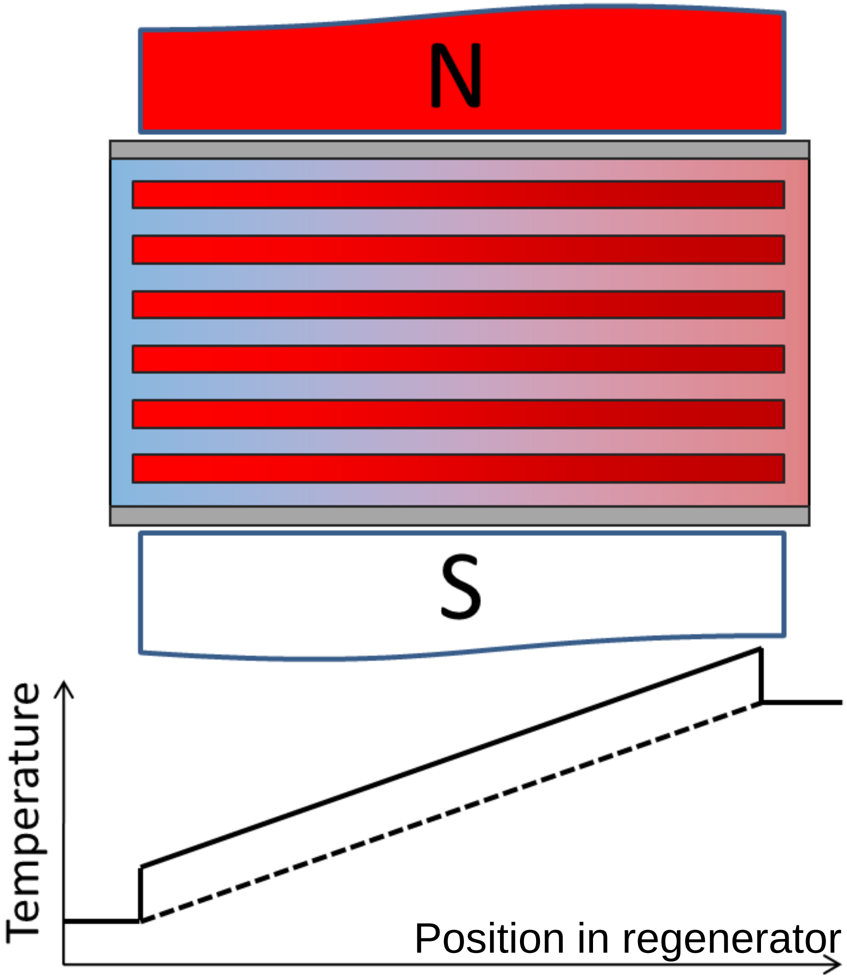
"MagQueen" the ENOVHEAT magnetocaloric heat pump prototype

Magnetocaloric heat pump
Active magnetic regenerator cycle



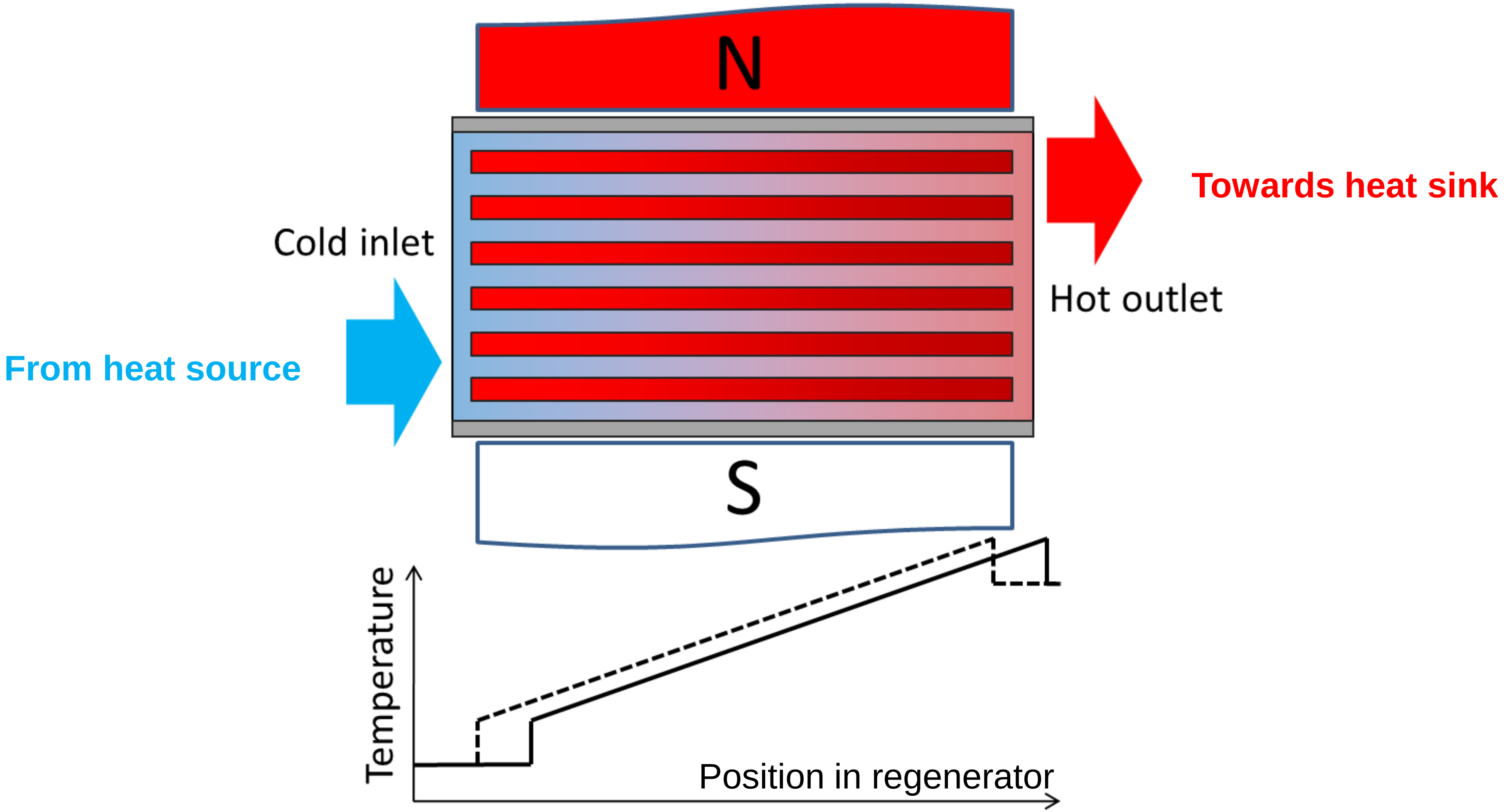
Active magnetic regenerator cycle: Initial state with temperature gradient

Magnetocaloric heat pump
Active magnetic regenerator cycle



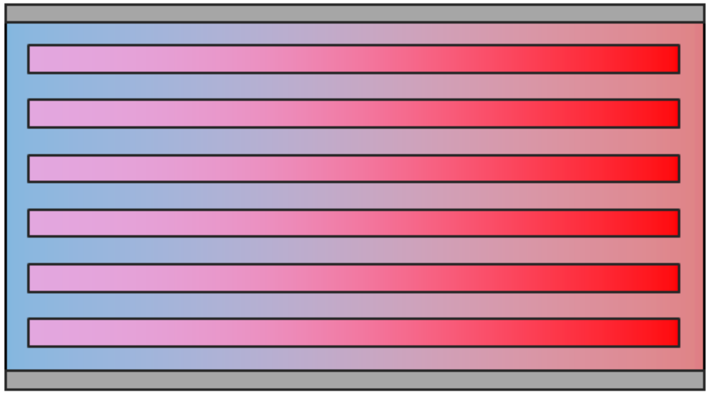
Active magnetic regenerator cycle: adiabatic magnetization

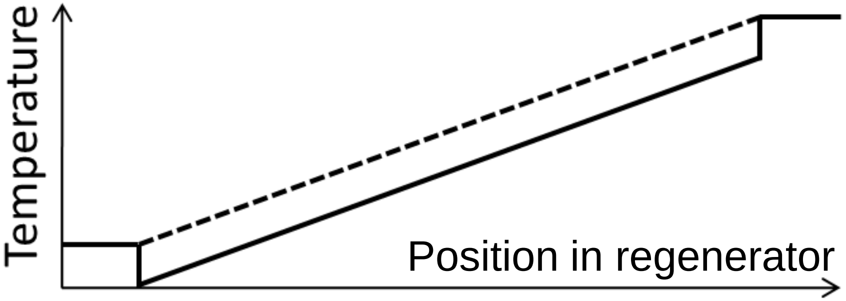
Magnetocaloric heat pump
Active magnetic regenerator cycle



Active magnetic regenerator cycle: cold-to-hot blow

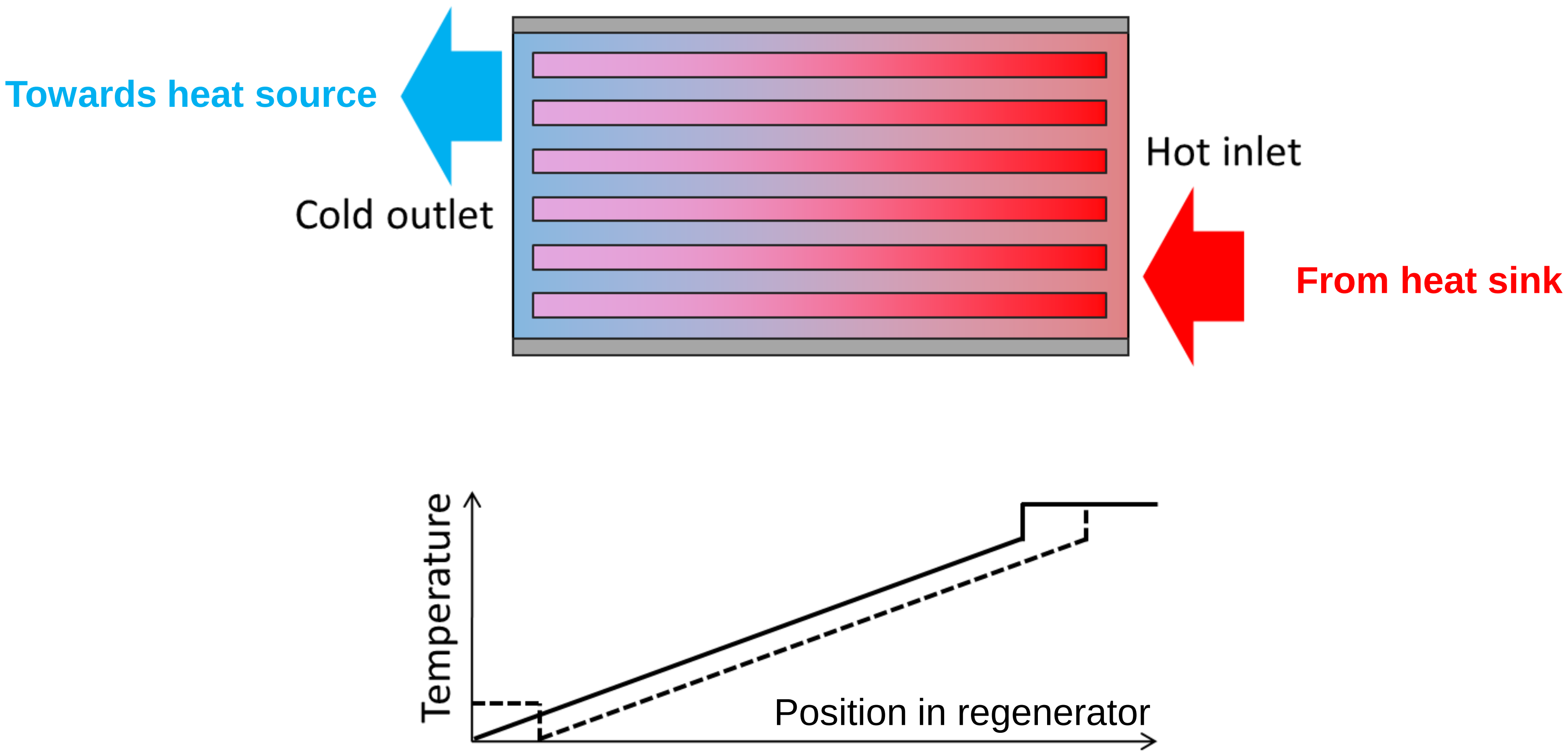
Magnetocaloric heat pump
Active magnetic regenerator cycle





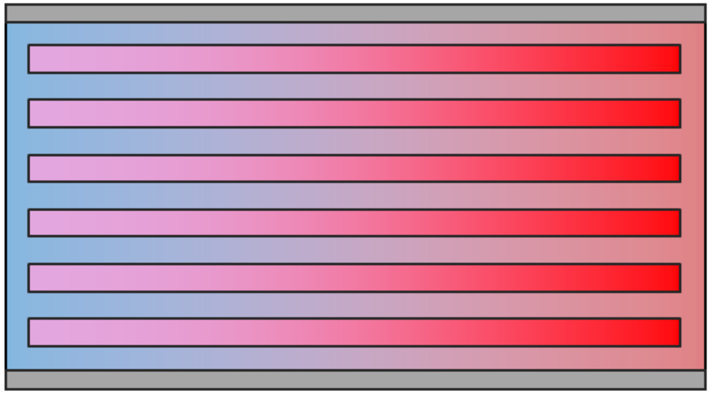
Active magnetic regenerator cycle: adiabatic demagnetization

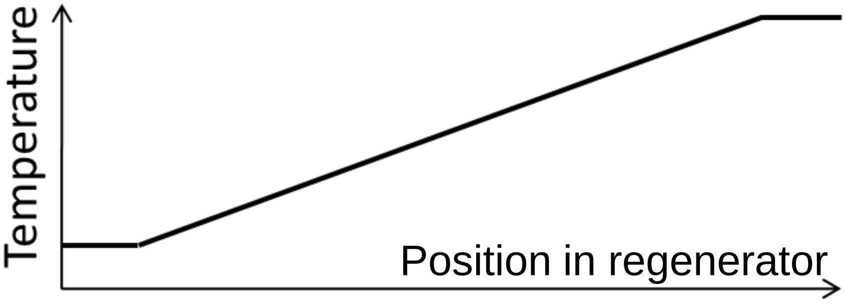
Magnetocaloric heat pump
Active magnetic regenerator cycle



Active magnetic regenerator cycle: hot-to-cold blow (regeneration)

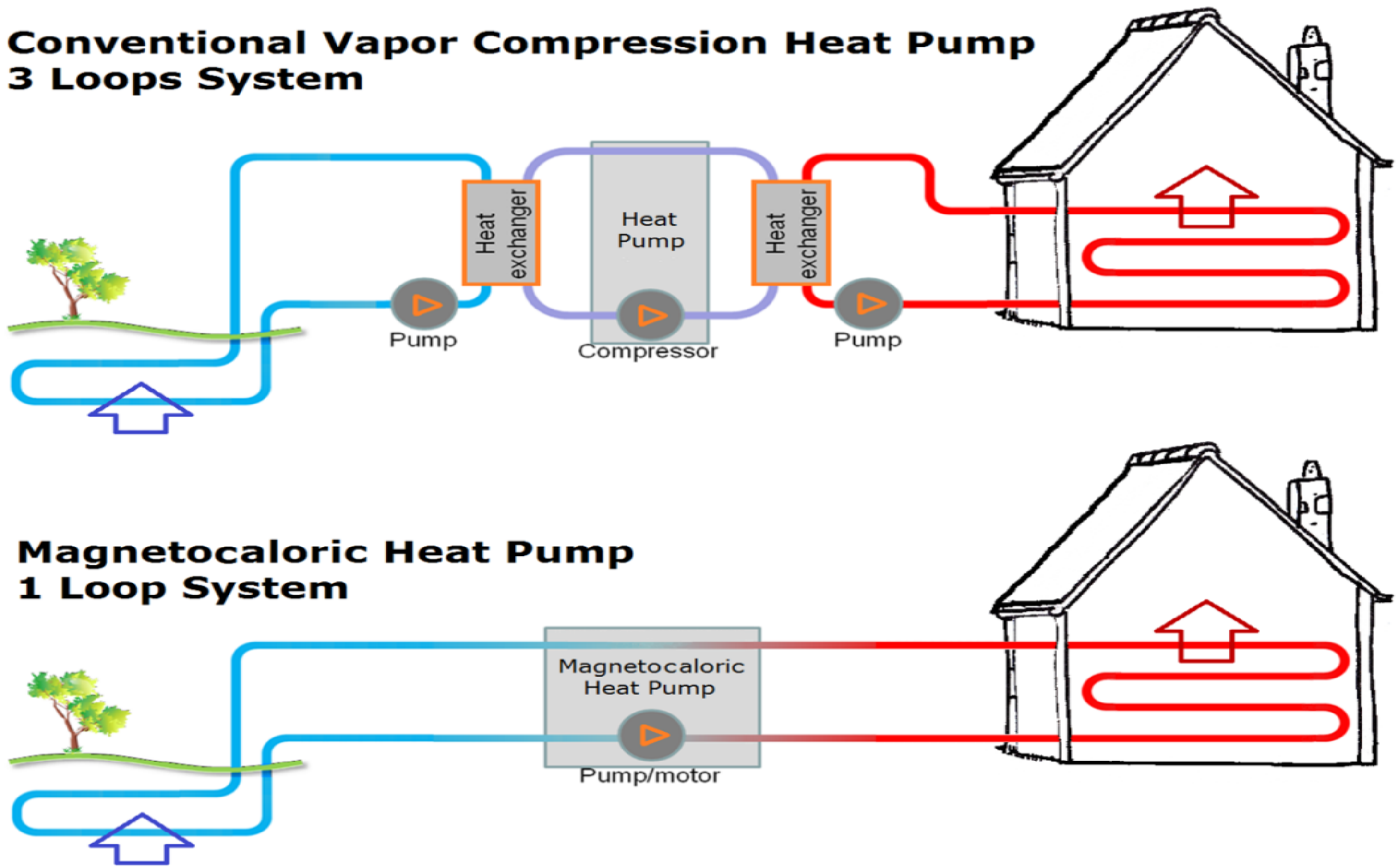
Magnetocaloric heat pump
Active magnetic regenerator cycle





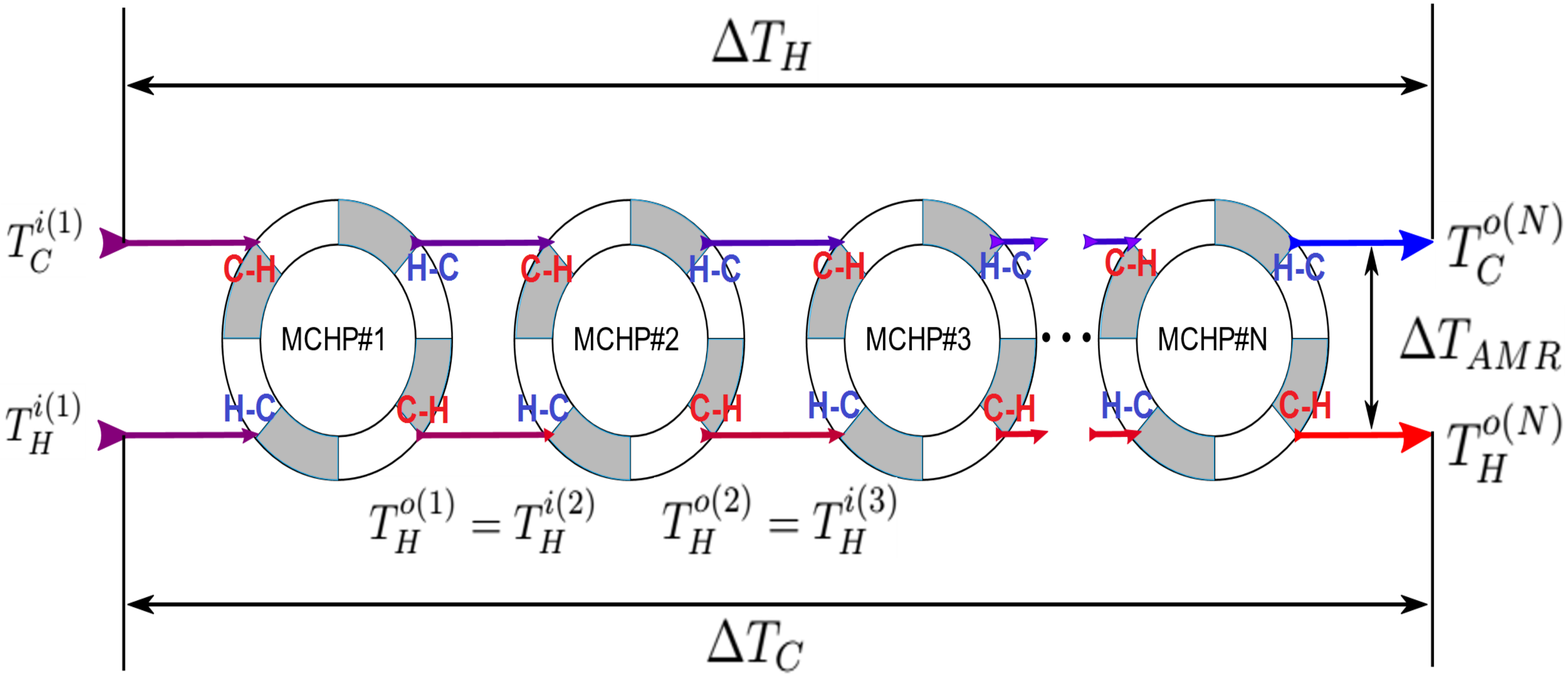
Active magnetic regenerator cycle: back to initial state

Heat pump implementation



Conventional and magnetocaloric heat pump implementation in buildings

Cascading regenerators



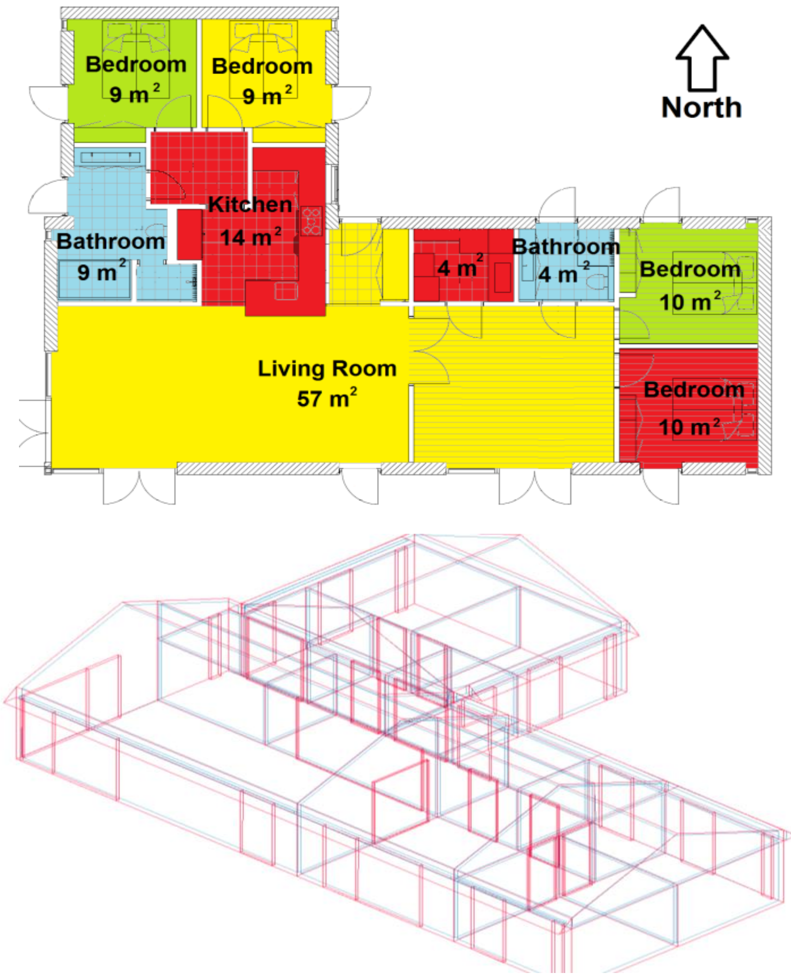
Cascading connection diagram (hot-to-hot and cold-to-cold)

Objectives of the numerical study

- Integrate the magnetocaloric heat pump in a Danish residential building to provide space heating (no DHW)
- Test 2 different magnetocaloric materials:
  - Gadolinium
  - $La(Fe,Mn,Si)_{13}H_y$
- Test different cascading configurations for higher temperature span for poorly-insulated buildings

Building study cases

- Danish single-family house
- Low / high space heating needs
- Radiant under-floor heating
- Vertical borehole ground source heat exchanger
- Winter / spring season



A typical danish house

Heat pump study cases

Different cascading configurations (same mass of magnetocaloric material):

- Single heat pump with Gadolinium (24 regenerators)
- Single heat pump with $La(Fe,Mn,Si)_{13}H_y$ (24 regenerators)
- 12 cascaded heat pumps with Gadolinium (2 regenerators each connected in parallel)
- 4 cascaded heat pumps with $La(Fe,Mn,Si)_{13}H_y$ (6 regenerators each connected in parallel)

Magnetocaloric heat pump modelling

AMR model: Engelbrecht and Lei

$$\frac{\partial}{\partial x}\left(k_{\mathrm{disp}}A_c\frac{\partial T_f}{\partial x}\right)-\dot{m}_f c_f\frac{\partial T_f}{\partial x}-\frac{Nuk_f}{d_h}a_s A_c\left(T_f-T_s\right)+\left|\frac{\partial P}{\partial x}\frac{\dot{m}_f}{\rho_f}\right| = A_c\varepsilon\rho_f c_f\frac{\partial T_f}{\partial t}$$

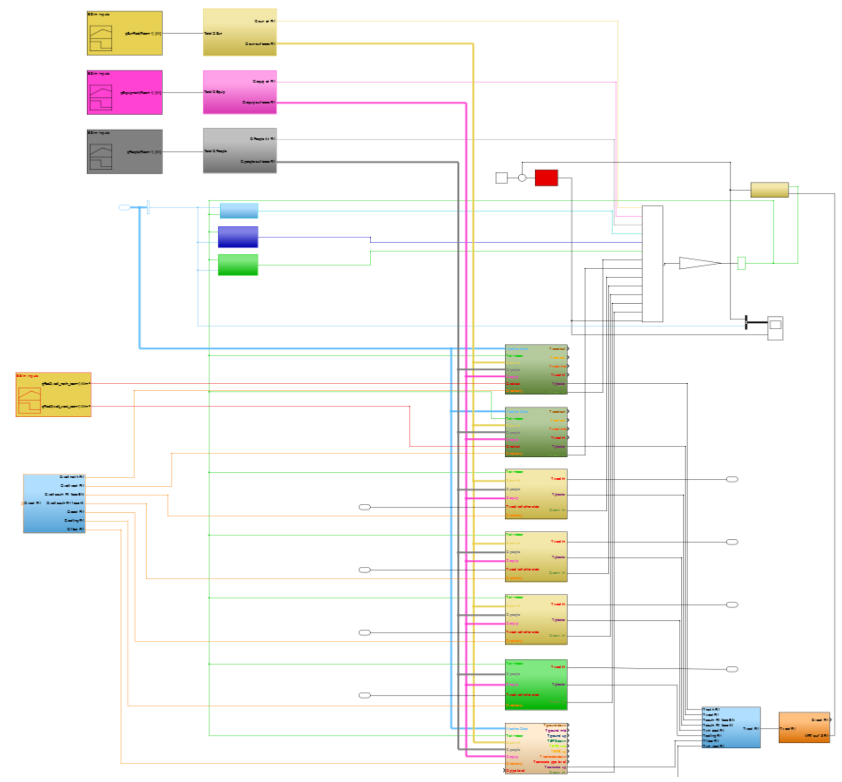
$$\frac{\partial}{\partial x}\left(k_{\mathrm{stat}}A_c\frac{\partial T_s}{\partial x}\right)+\frac{\mathrm{Nu}k_f}{d_h}a_s A_c\left(T_f-T_s\right) = A_c\left(1-\varepsilon\right)\rho_s\times\left[c_H\frac{\partial T_s}{\partial t}+T_s\left(\frac{\partial s_s}{\partial H}\right)_{T_s}\frac{\partial H}{\partial t}\right]$$

→ 5-dimensional lookup tables with 1600 points

Building modelling

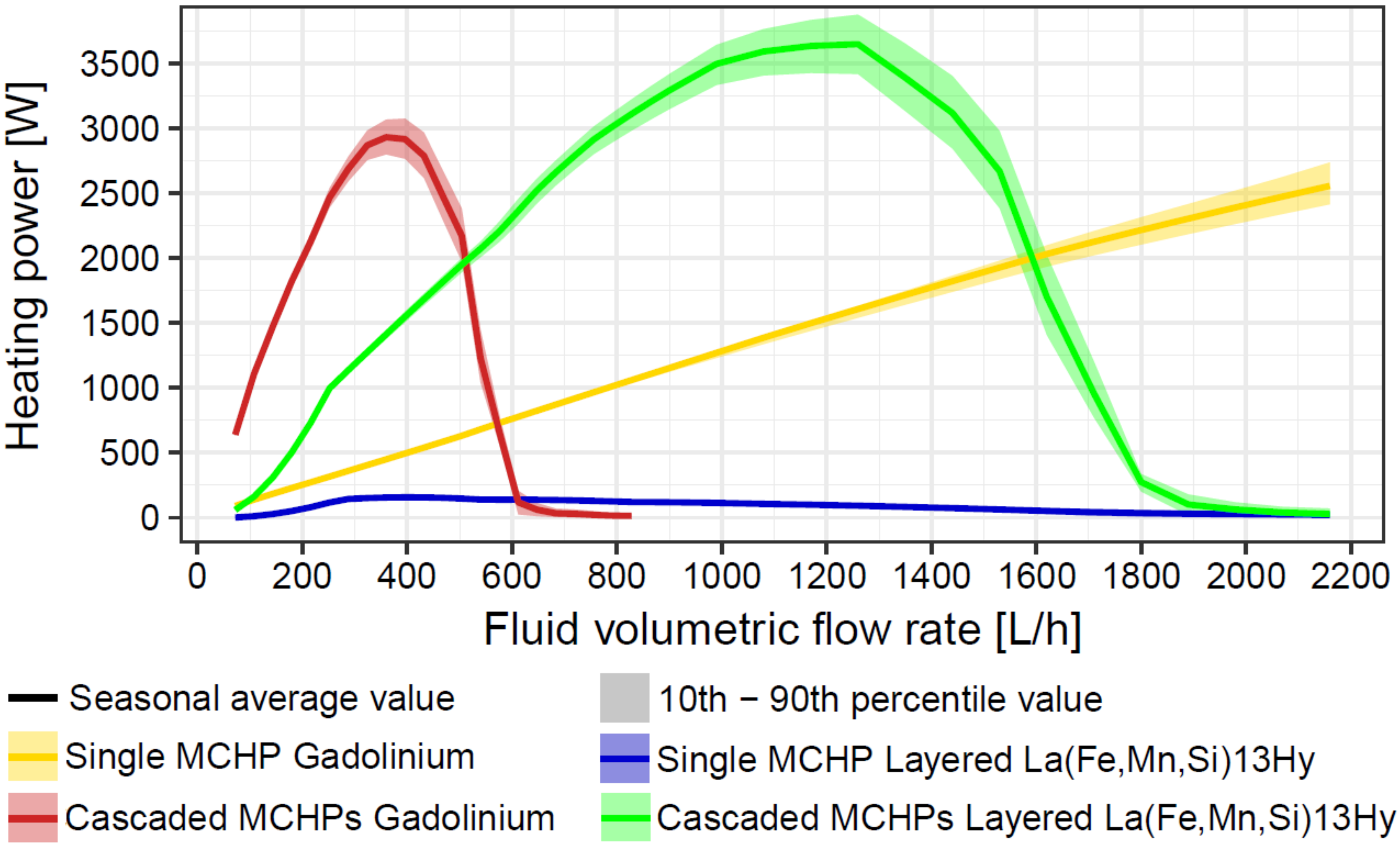
- Multi-zone building model of the house developed with *MATLAB-Simulink*

- Hydronic systems (under-floor heating and ground source) with *ε-NTU* model combined with *plug-flow* model



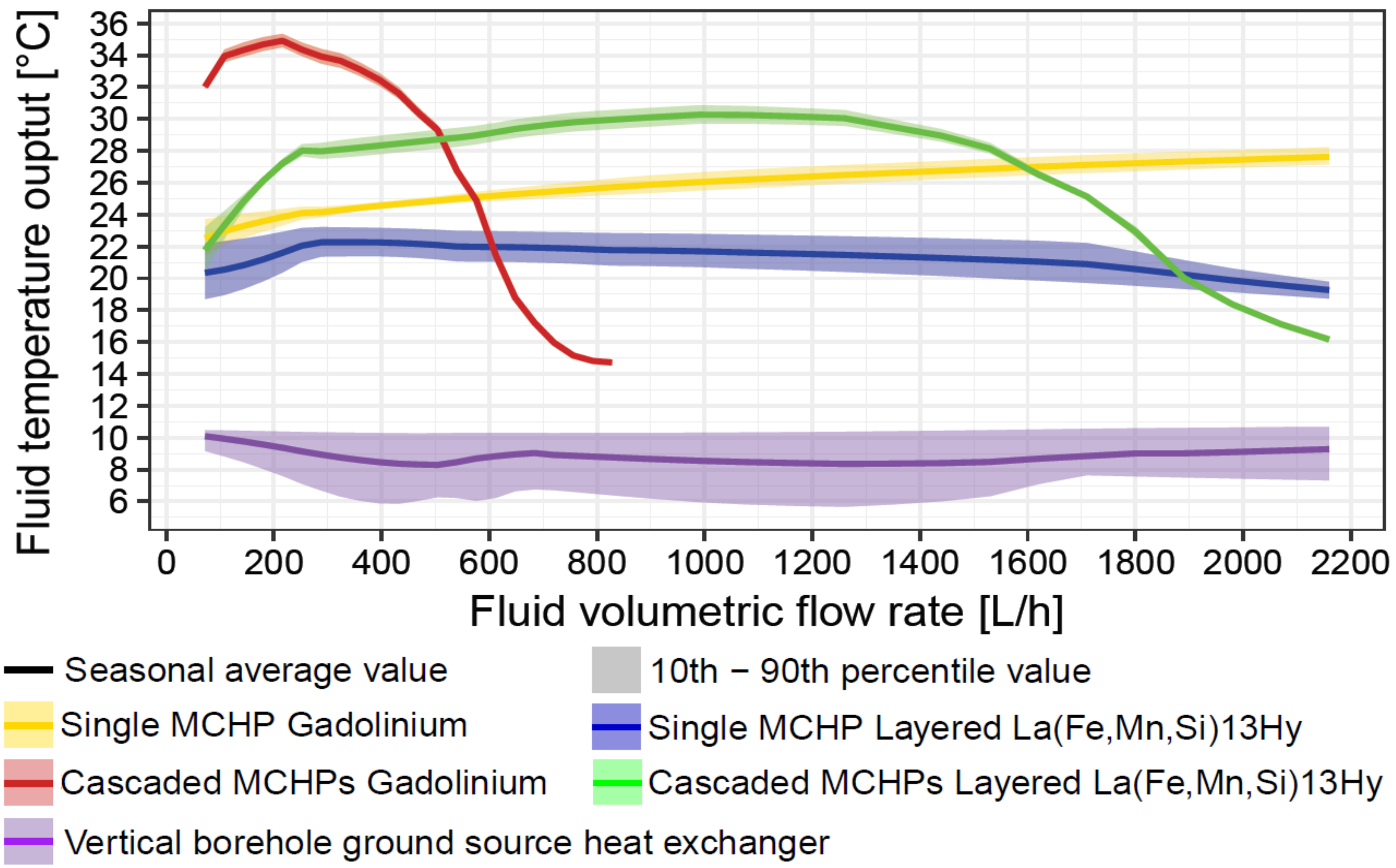
MATLAB-Simulink building model

Numerical study: results



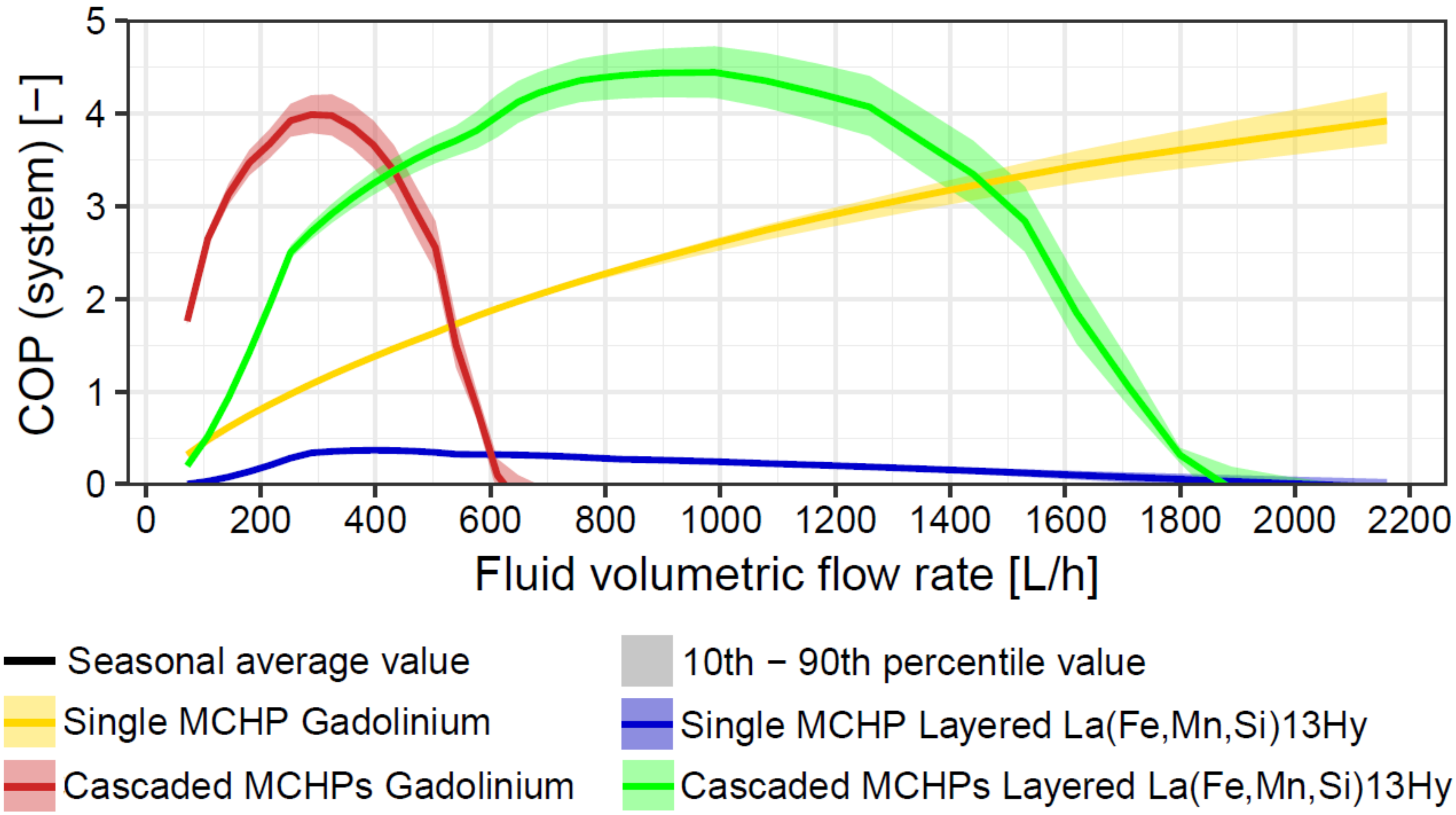
Heating power production as function of fluid flow rate

Numerical study: results



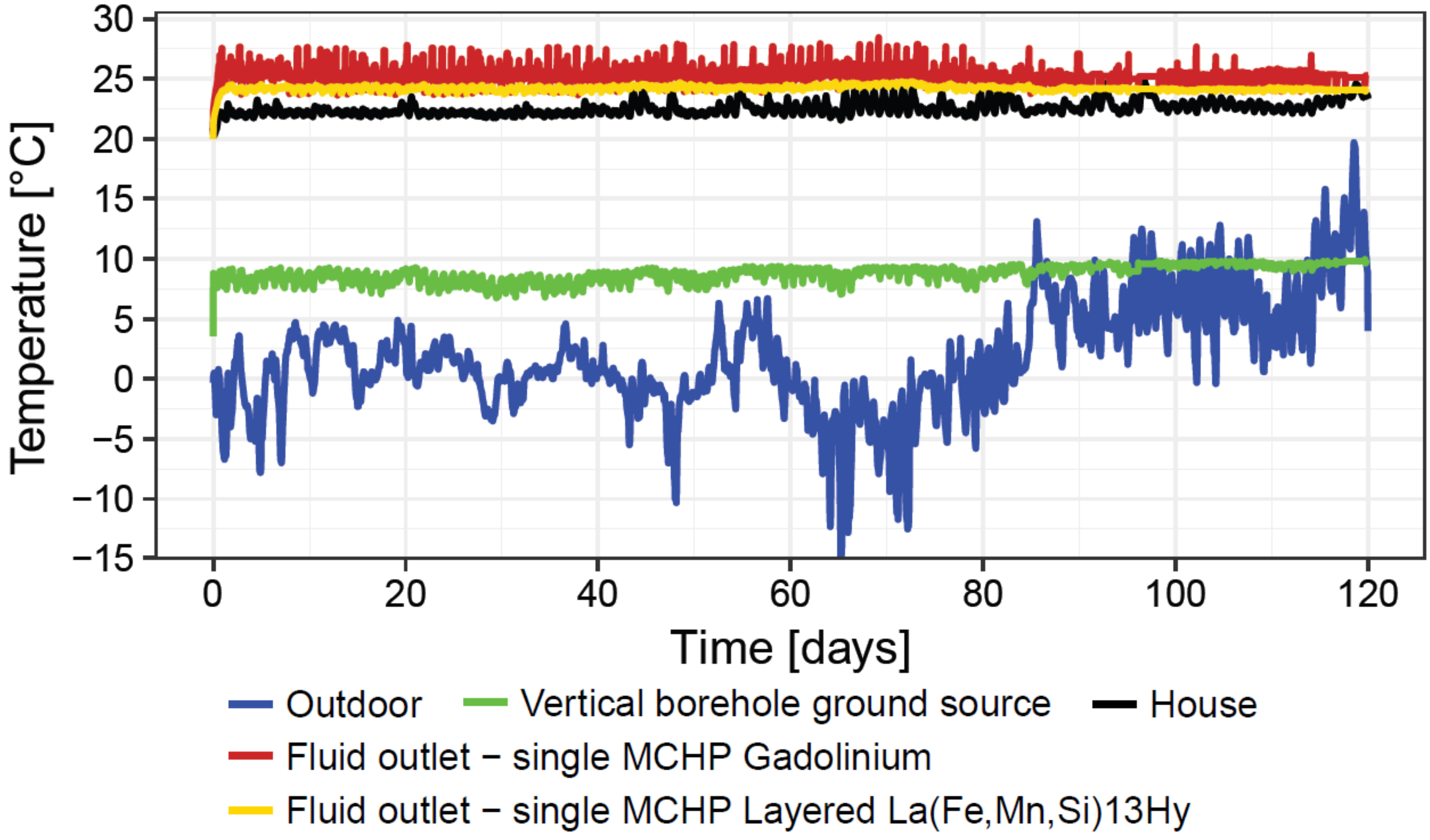
Fluid temperature as function of fluid flow rate

Numerical study: results



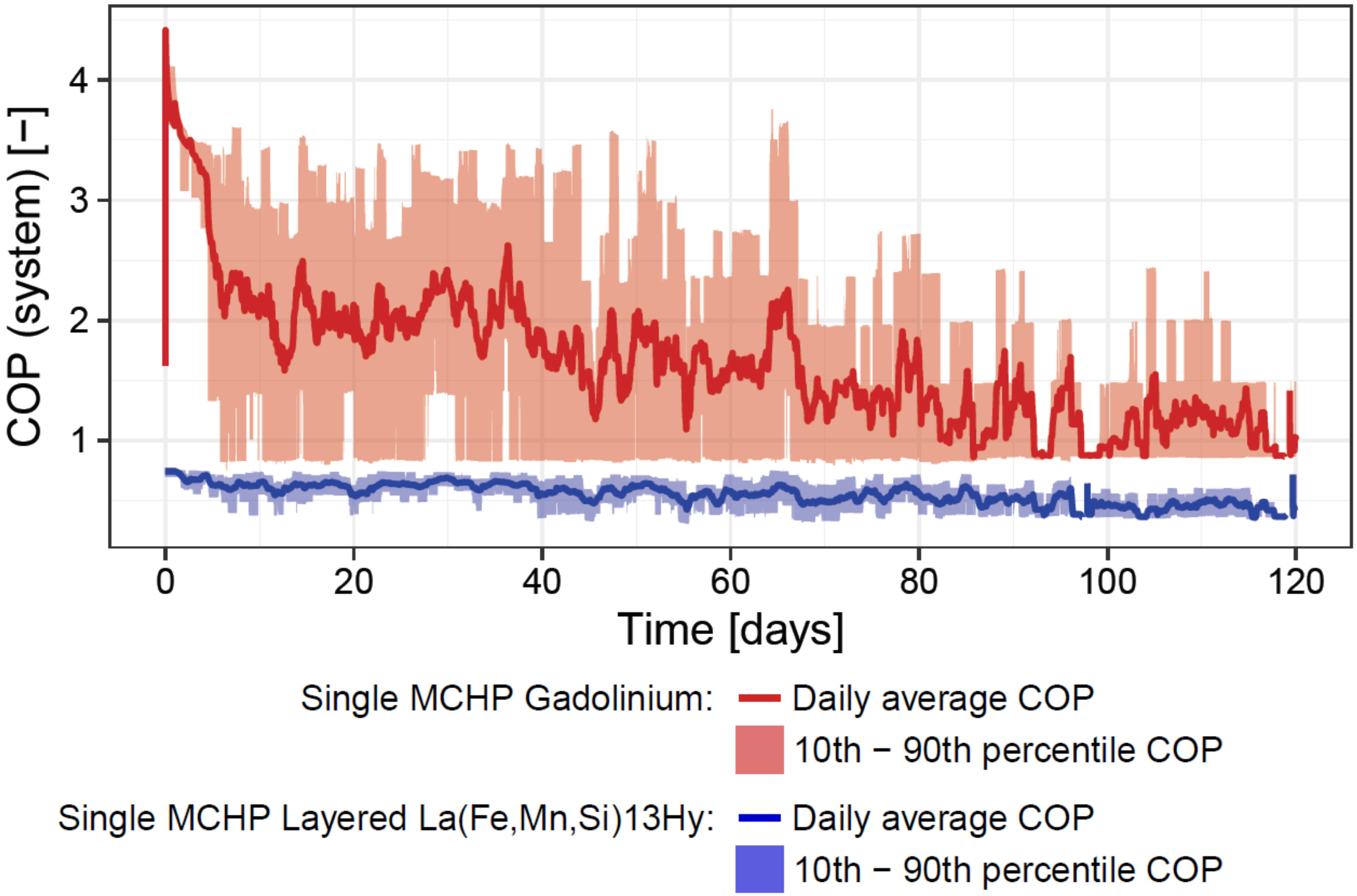
COP entire heating system as function of fluid flow rate

Numerical study: results



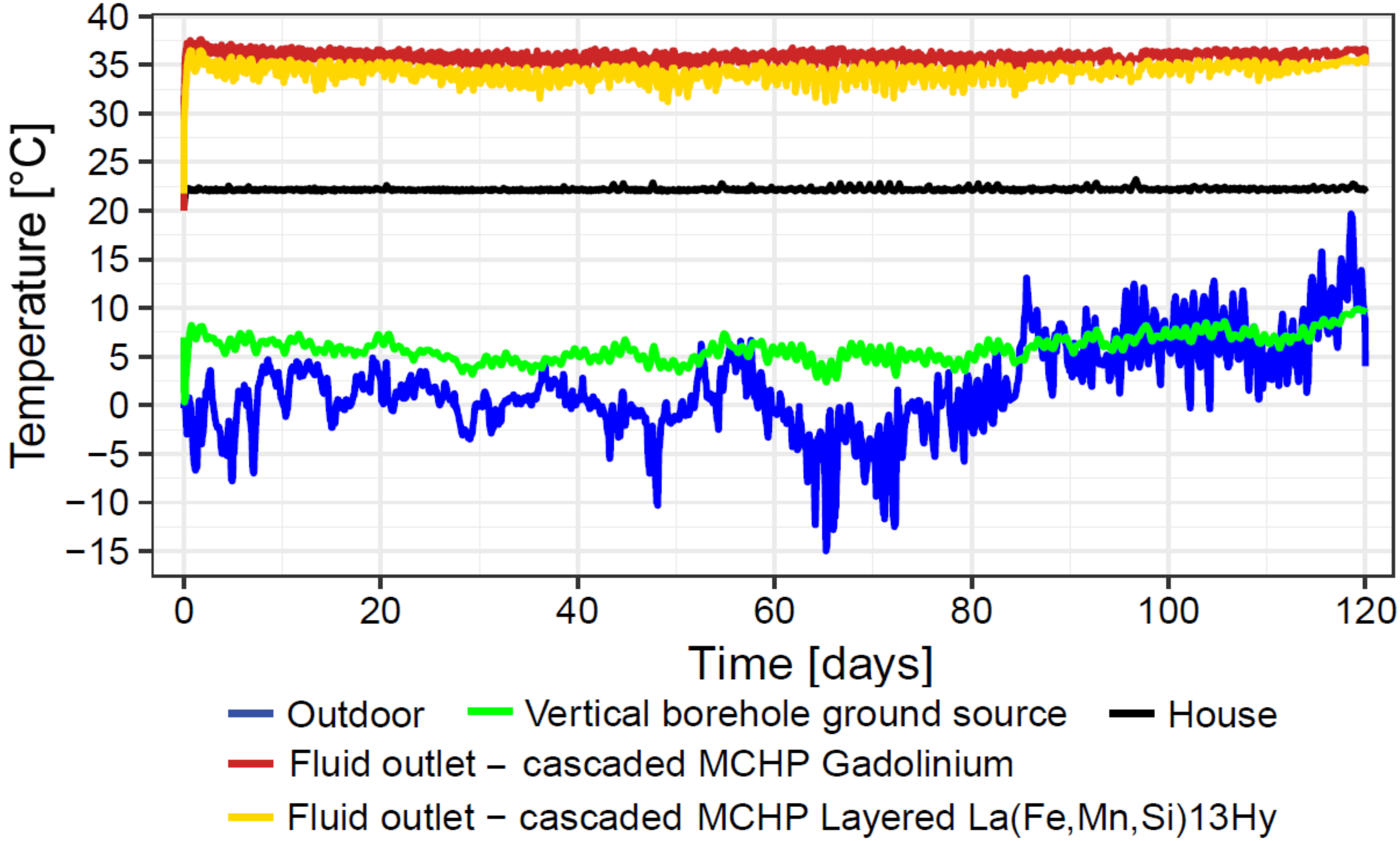
Temperatures during heating period: well-insulated house with single heat pumps

Numerical study: results



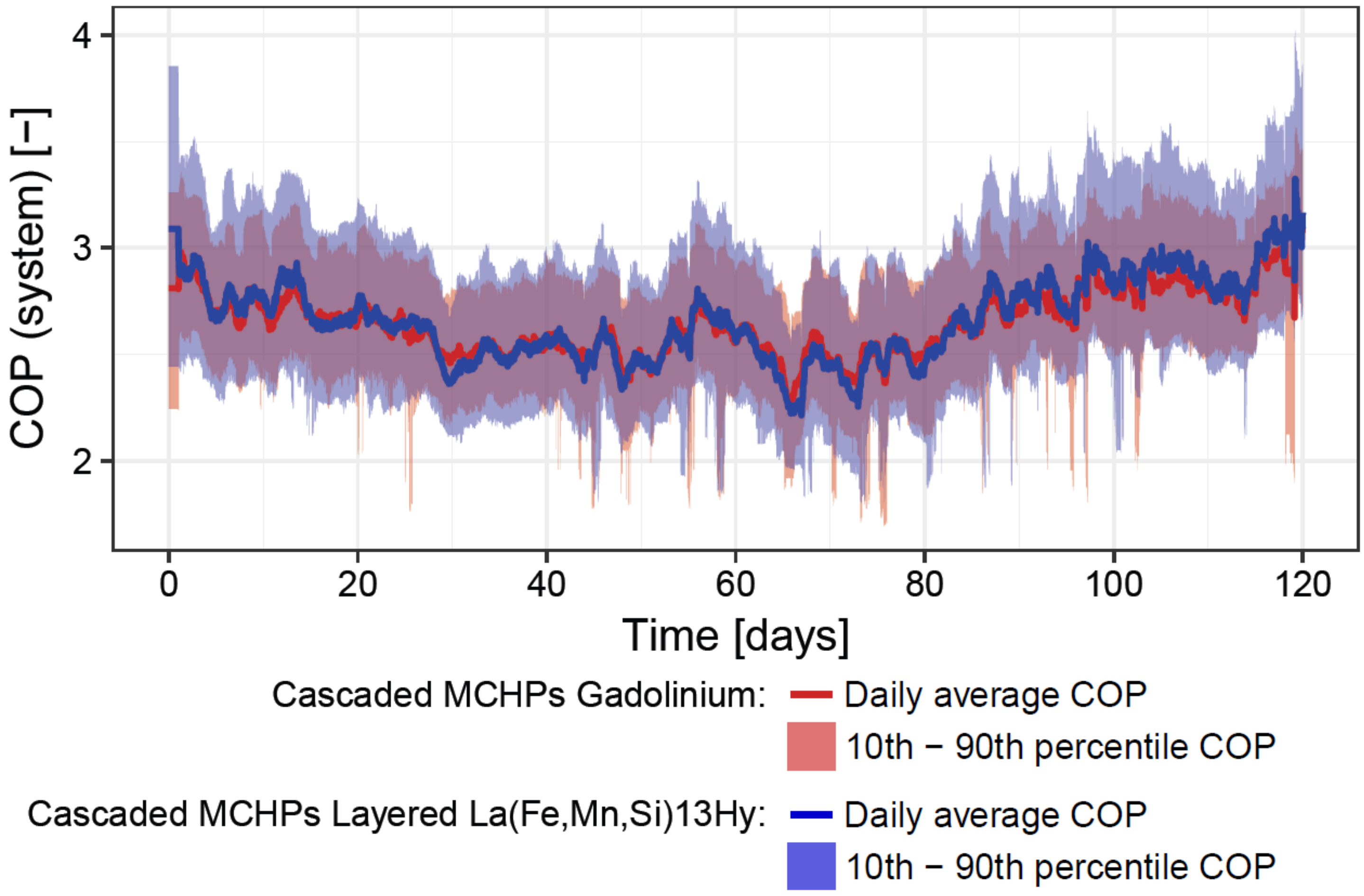
COP during heating period: well-insulated house with single heat pumps

Numerical study: results



Temperatures during heating period: poorly-insulated house with cascaded heat pumps

Numerical study: results



COP during heating period: poorly-insulated house with cascaded heat pumps

Conclusions

- A magnetocaloric heat pump system can be used for indoor space heating application in buildings
- It can operate in a single hydronic loop with under-floor heating system and ground source
- For single Gadolinium system, nominal COP at maximum flow is similar to conventional heat pumps
- However, part load operation leads to poor seasonal COP
- Single $La(Fe,Mn,Si)_{13}H_y$ system has modest performance due to its limited heating power output
- Cascaded heat pumps show appreciable temperature spans with good seasonal COPs for space heating

Recommendations for future work

- Full scale experimental tests for building applications
- Improve performance of magnetocaloric material compounds
- New designs for minimizing pressure, heat, friction and magnetic losses
- Test new hydronic configurations for heating purpose
- Develop efficient control strategies to keep heat pump operation within conditions for best COPs
- Cascading implementation for domestic hot water production
- Testing elastocaloric heating / cooling systems

Thank you for your attention !
Any questions ?

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