# HT-ATES with Buoyancy Flow as a System Model in Modelica

INSTITUTE OF ENGINEERING THERMODYNAMICS

TUHH
Hamburg University of Technology

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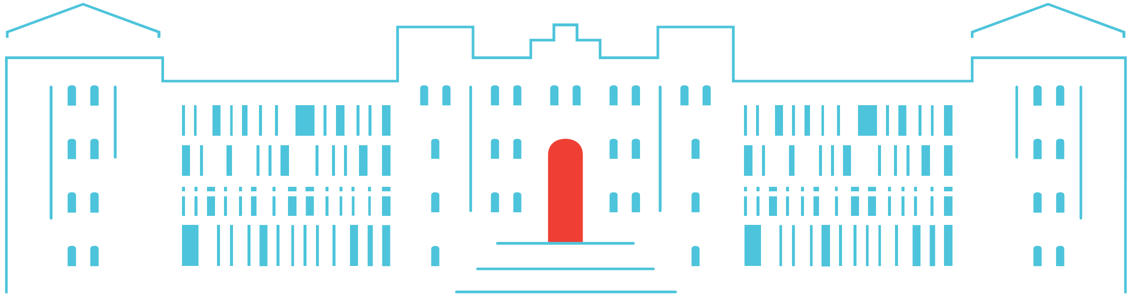


Markus Gillner, Prof. Arne Speerforck

# Agenda

1. Introduction of TV8.2 in the Northern German Living Lab
2. Presentation of the ATES Modelica Model
3. Results of Validation
4. Summary

# TV8.2: Design and construction of an ATES for the seasonal storage of waste and surplus heat

**Targets:**

- Pilot project of an HT-ATES
- Integration into the district heating network

**Partners:**

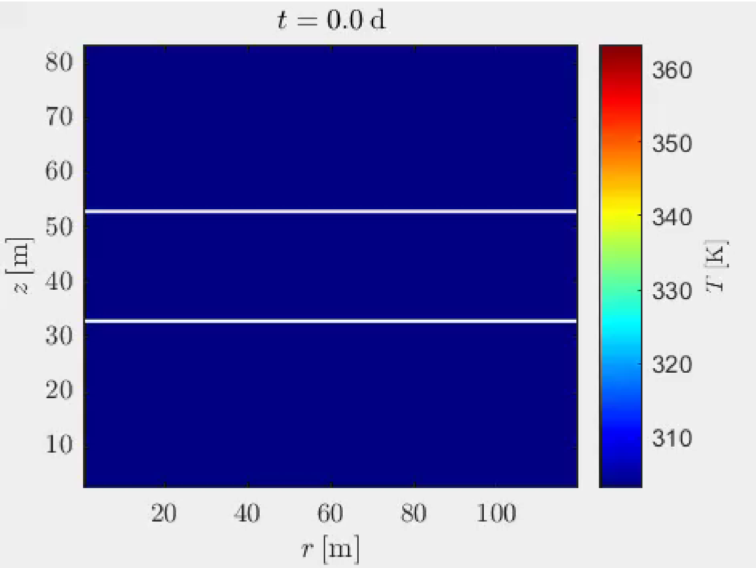
- Hamburger Energiewerke GmbH: Construction and operation of the HT-ATES
- Institute of Engineering Thermodynamics (TUHH): Modelling of the ATES and the above-ground facility, Validation of the models based on measurement data
- Christian-Albrechts-University (Kiel): Accompanying scientific research on gas solubility and salt precipitation


Key Facts:

- Power: 2.6 MW (10.4 MW)
- Capacity: 5 GWh (20 GWh)
- Injection temperature: 90℃
- Depth: 1200m

Cancellation of construction due to low productivity

# Motivation: ATES as a system model




Temperature distribution in an aquifer with buoyancy during the 1st cycle

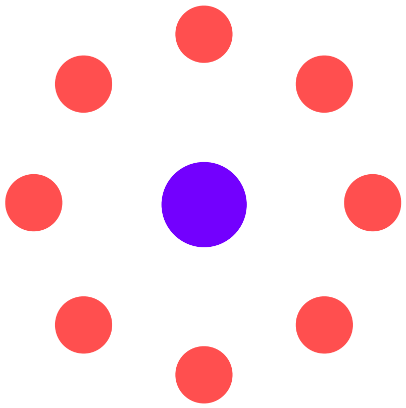
- Buoyancy flow significantly impacts efficiency
- Estimating the impact through
  - Critical Rayleigh-Darcy number
  - Dimensionless study of Gao et al.[2]
- Available models:
  - TRNSYS: TRNAST[3] model
  - Modelica: model of Maccarini et al.[4]

Buoyancy is neglected

Need for a system model that takes buoyancy flow into account.

[2]Gao, H. et al. (2024). "Estimation of Recovery Efficiency in High-Temperature Aquifer Thermal Energy Storage Considering Buoyancy Flow". In: Water Resources Research 60.11.
[3]Schmidt, Thomas (2005). Aquifer Thermal Energy Storage – TRNAST Two Well Model for TRNSYS. Tech. rep. Stuttgart: Solites - Steinbeis Research Institute for Solar and Sustainable Thermal Energy System
[4]Maccarini, Alessandro et al. (2023). "Low-order aquifer thermal energy storage model for geothermal system simulation". In: Linkoping Electronic Conference Proceedings. Linkoping University Electronic Press, pp. 389–396.

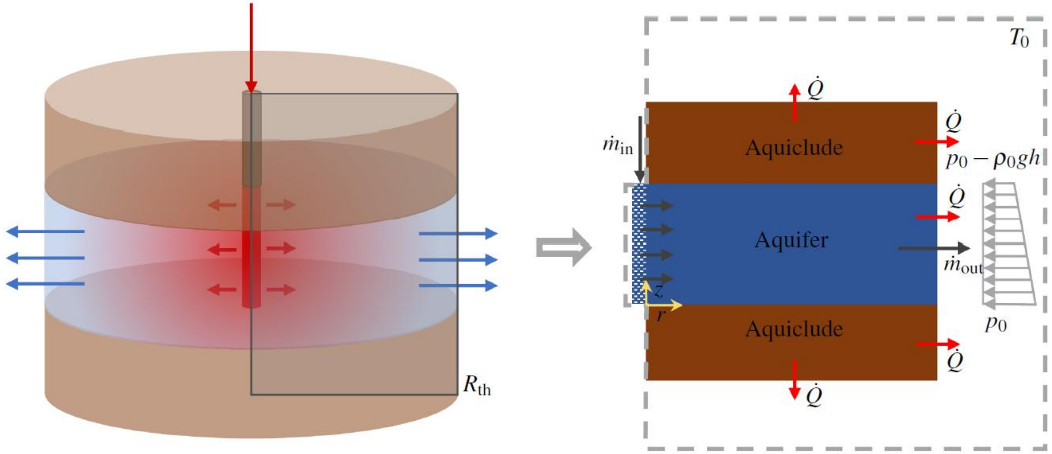
# Model development and validation



# Assumptions and physics

## Assumptions of the model

- The subsurface is homogeneous and isotropic (axisymmetric)
- No natural regional groundwater flow
- Single well model
- Local thermal equilibrium
- Fluid in the aquifer is assumed to be pure water
- Porosity, permeability, thickness of layers and solid material properties are constant




Abstraction of the model

**Momentum balance (Darcy equation):**

$$\boldsymbol{v} = -\frac{\boldsymbol{K}}{\mu}\left(\nabla p - \underbrace{\boxed{\rho_f \boldsymbol{g}}}_{\text{Buoyancy term}}\right)$$

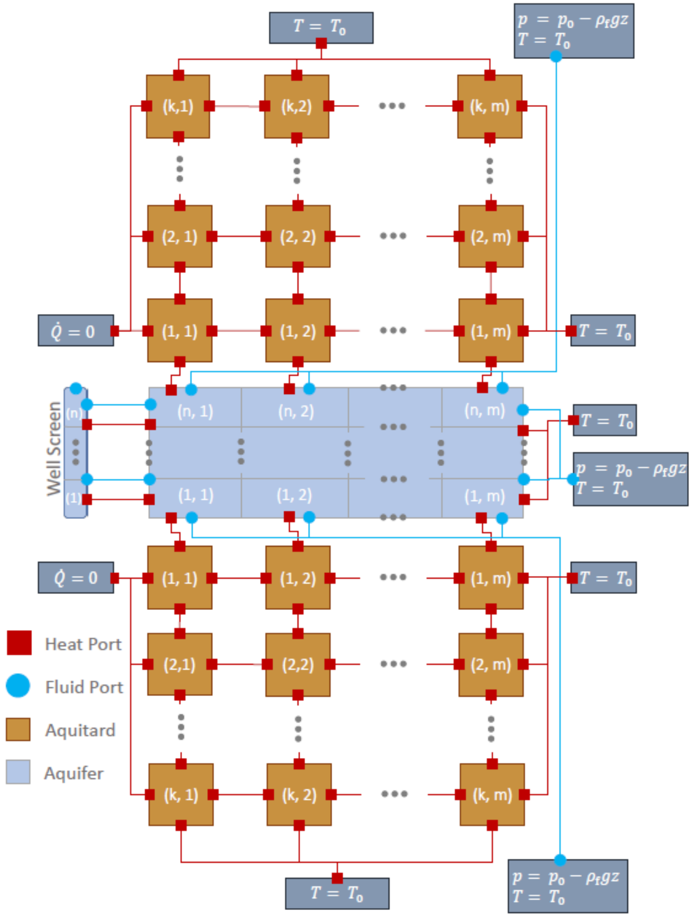
**Continuity equation:**

$$\phi \cdot \frac{\partial \rho_{\mathrm{f}}}{\partial t} + \nabla \cdot (\rho_f \cdot \boldsymbol{v}) = 0$$

**Energy balance:**

$$(\rho c_{\mathrm{p}})_{\mathrm{a}} \frac{\partial T}{\partial t} + \underbrace{(\rho c_{\mathrm{p}})_{\mathrm{f}} \cdot \boldsymbol{v} \cdot \nabla T}_{\text{Convection}} = \underbrace{\boldsymbol{k}_{\mathbf{eff}} \cdot \nabla(\nabla T)}_{\text{Diffusion}}$$

# Modelling



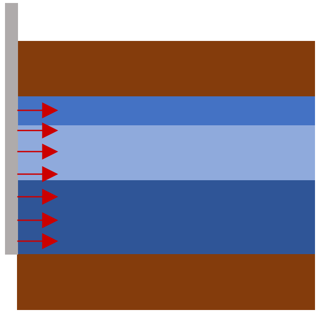

Schematic structure of the model[5]

## Modularity of the model

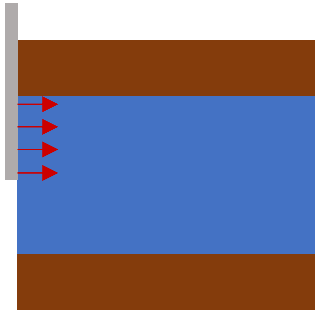

Buoyancy


Dispersion

Optional physical effects



Layering of different permeabilities



Well screen height

Geological factors and design decisions

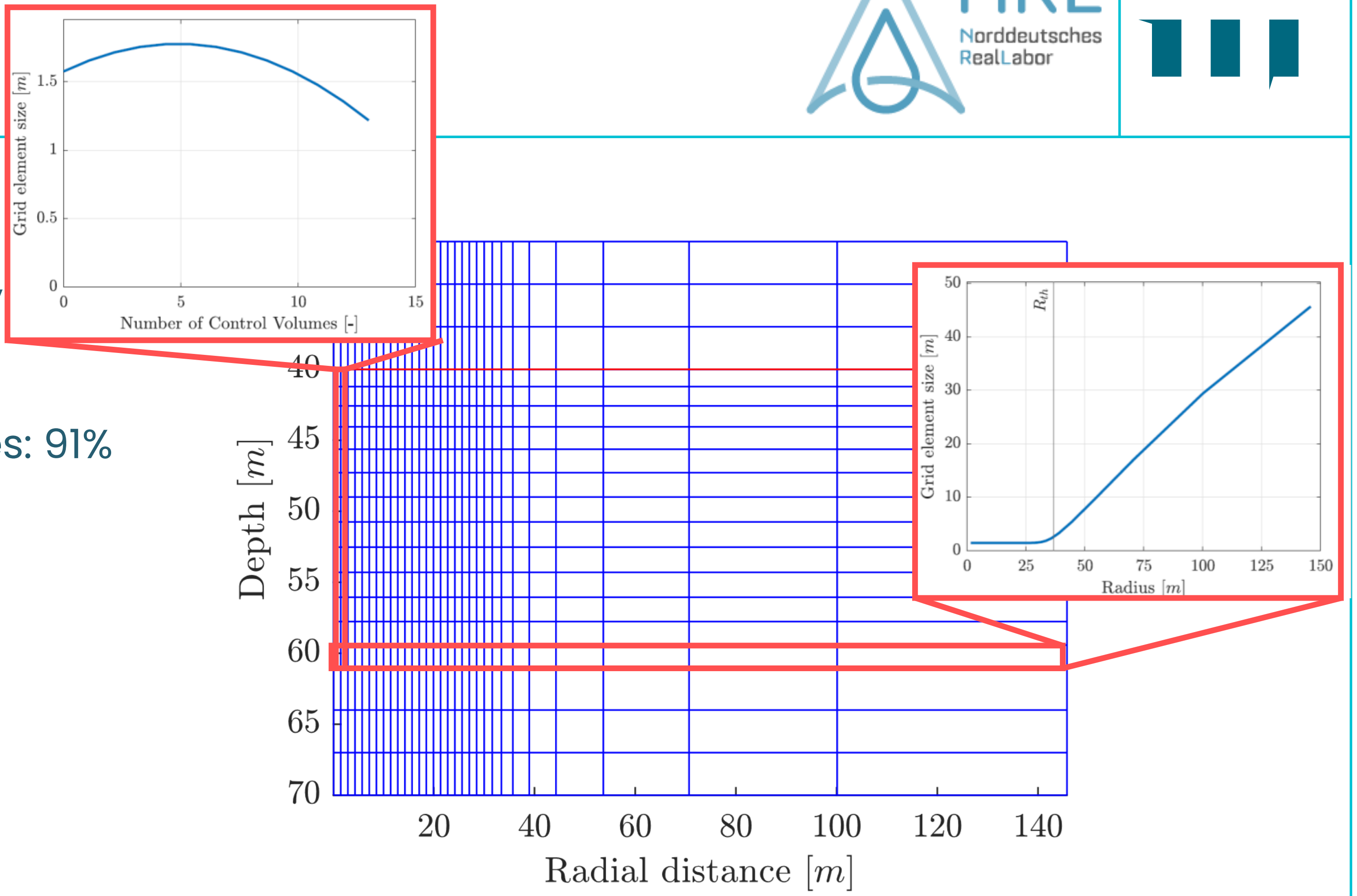
[5]Gillner, Markus, and Arne Speerforck. "Modelling Aquifer Thermal Energy Storage (ATES) System with Buoyancy Flow." Modelica Conferences. 2025.

# Grid optimisation

Reference model: 26,520 equidistant control v

After mesh optimisation:

- Reduction in the number of control volumes: 91% (2,340)
- Reduction in simulation time: 94%
- New simulation time: 20 s for 120 days
- Mean absolute deviation of the wellhead temperature from the reference: 0.089 K

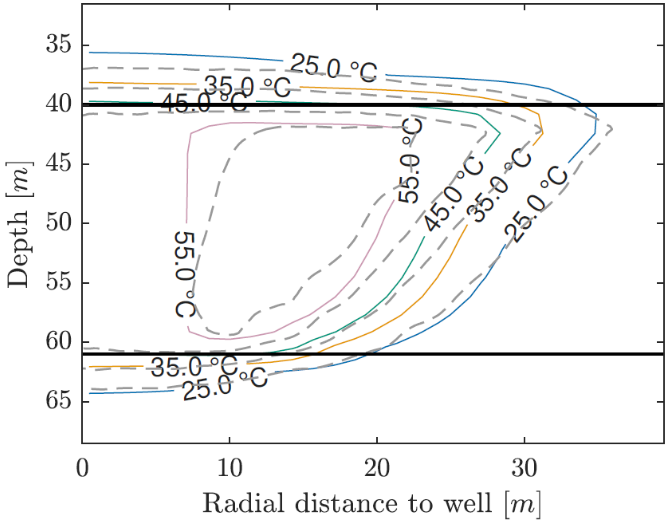



Optimised grid in the radial and vertical directions for an example aquifer

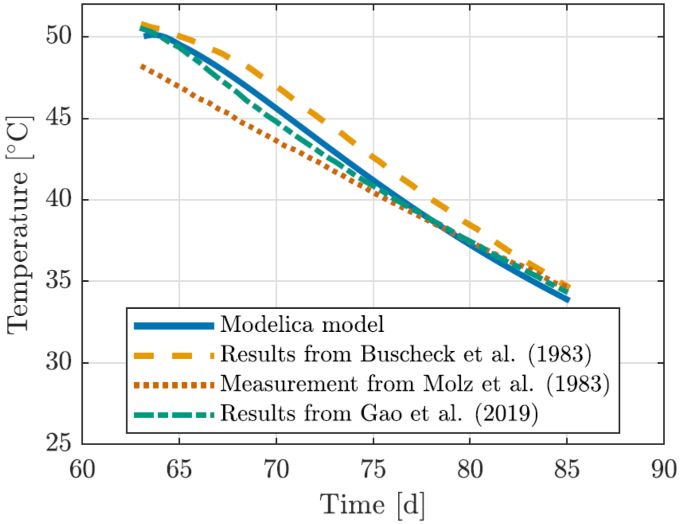
Significant reduction in computing time while maintaining very good model accuracy

# Validation – Comparison with experiment and other numerical programs

- Experiment at Auburn University in 1983[6]
  - Storage cycle of 120 days
  - 60℃ Injection temperature
- Numerical simulation:
  - Buscheck et al. (1983)[7]
  - Gao et al. (2019)[8]




Temperature distribution following the injection phase. Simulation according to Buscheck[7] (dashed line), Modelica simulation (solid line)




Wellhead temperature during the production phase

Very good agreement with the significantly more detailed 3D FEM model by Gao et al. (2019)[8]

[6]Molz, F. J., Melville, J. G., Parr, A. D., King, D. A., & Hopf, M. T. (1983). Aquifer thermal energy storage: a well doublet experiment at increased temperatures. Water Resources Research, 19(1), 149-160

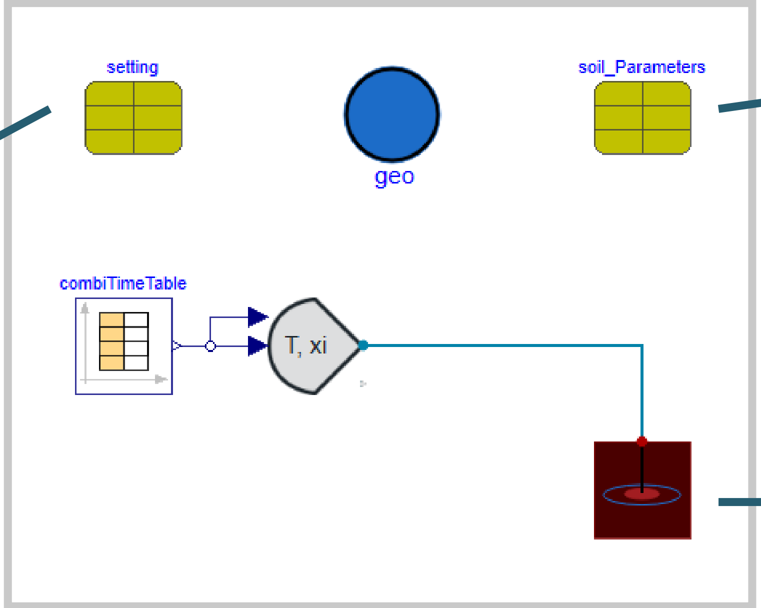
[6]Buscheck, Thomas A., Christine Doughty, and Chin Fu Tsang (1983). "Prediction and analysis of a field experiment on a multilayered aquifer thermal energy storage system with strong buoyancy flow". In: Water Resources Research 19.5, pp. 1307–1315.

[8]Gao, L., Zhao, J., An, Q., Liu, X., & Du, Y. (2019). Thermal performance of medium-to-high-temperature aquifer thermal energy storage systems. Applied Thermal Engineering, 146, 898-909.

# Summary of the model

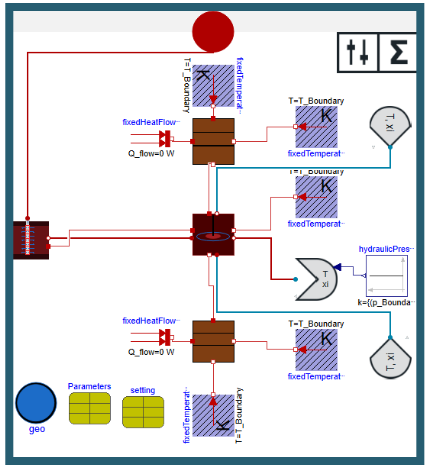
User decisions:

- Optional physical effects
- Optimised or manual grid




Graphical interface of a test model in Modelica

List of all important soil parameters




Aquifer model

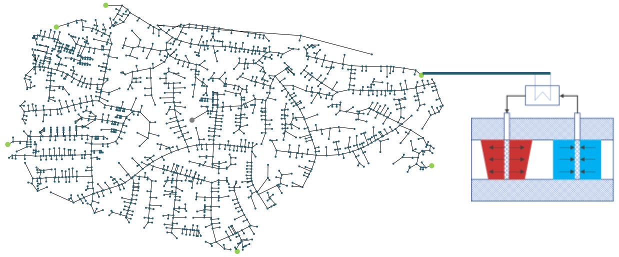
Will be published in the **TransiEnt Library**[9]

[9]Gillner, M., Westphal, J., Wiegel, B., Steffen, T., Urbansky, J., Hagemeier, A., ... & Speerforck, A. (2025, October). Status of the transient library: Transient simulation of complex integrated energy systems. In Modelica Conferences (pp. 989-999).

# Summary

# Summary

- Open-source ATES model for low- and high-temperature operation with high accuracy
  - Use for feasibility studies
  - Use for integration into the district heating network
  - Use for better understanding of buoyancy effects



# Questions are welcome!

Thank you for your attention!

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