Methodology development for accelerated generation of thermal energy storage models for transient system simulations

Towards more efficient modeling and simulation of large-scale hot-water underground pit and tank TES

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Content

- PhD thesis (Big Picture)
- Modeling and simulation of large-scale thermal energy storages (LTES)
  - Motivation
  - Model description
    - Overview
    - Fluid domain model
    - Soil domain model
  - Validation case study
    - Description
    - Results and conclusion
  - Further investigations and applications of the model
- Conclusion and outlook

PhD thesis (Big Picture)

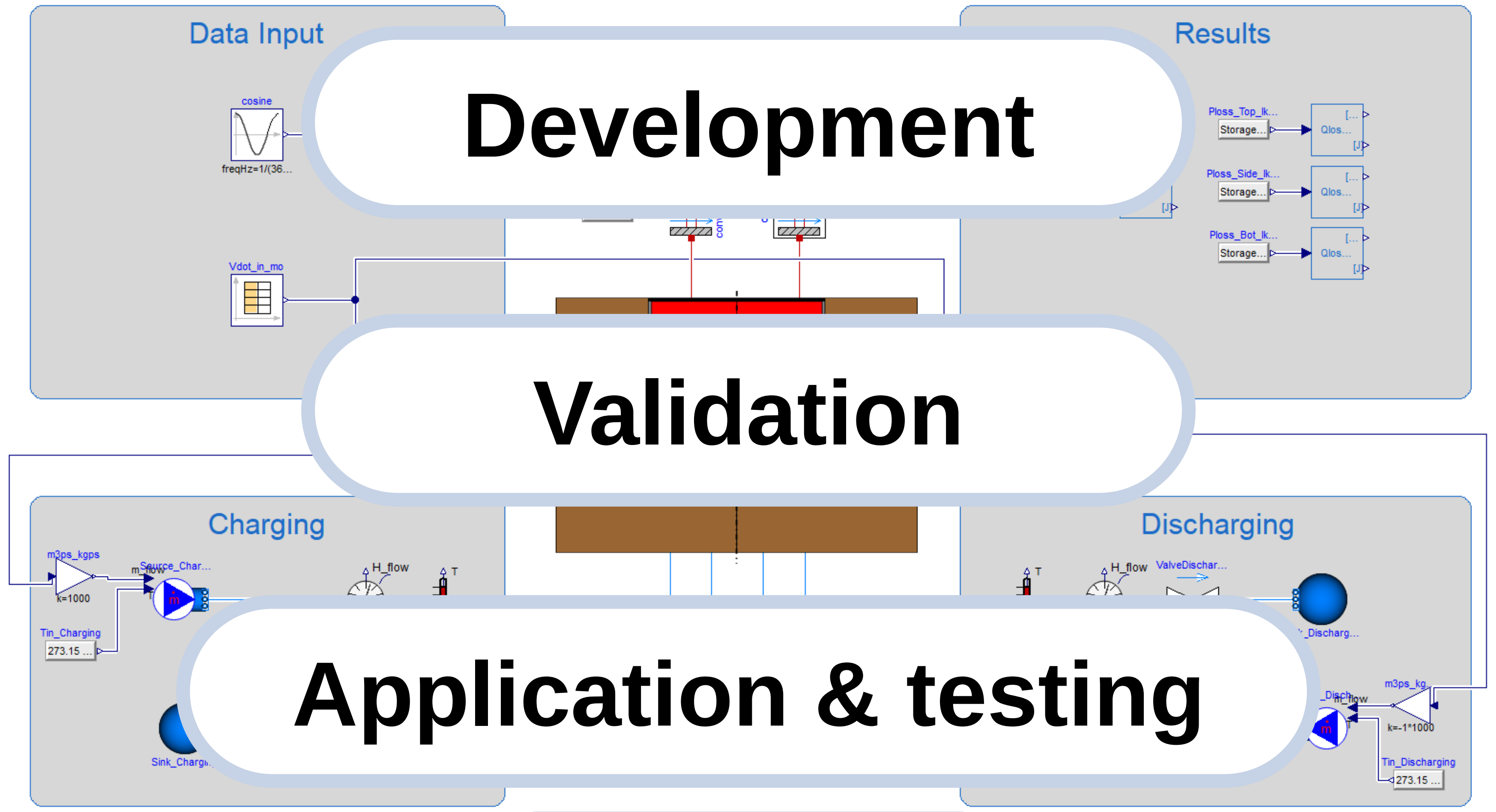
OVERALL AIM: Accelerated generation of new TES models

WHY?
 # Modeling process: Complex, time-consuming and costly
New emerging TES technologies and more complex energy systems → Multi-annual dynamic system simulations are necessary for proper design, integration and market launch of these new technologies

General procedures, guidelines & modeling toolboxes

Large-scale TES

Source: Arcon-Sunmark



Development

Validation

Application & testing

Thermochemical TES

Modelica Language

Open-source
Equation-based, object-oriented and hierarchical
High reusability, flexibility and expandability

Modeling and simulation of LTES: Motivation

Why large-scale hot-water underground tank and pit TES? [1]

Seasonal and short-term storage of renewable energy
Provision of peak load capabilities for power grids (Power2Heat) → Sector Coupling
"Potentially cheapest way to store thermal energy"
Attractive integration in urban environment possible ("no free-standing, high structures")
…

→ Central element of future district and local energy system in order to increase the share of volatile renewable energy sources

Why system simulations?

Increased no. of components and complexity of future systems
Long-term (multi-annual) investigations are necessary
Experiments practically limited to the component level
In general: for parameter studies, techno-economic analyses, ecological analyses, …

→ System simulations are necessary in order to fully exploit the potential of LTES technologies

Why Modelica? [2]

High reusability, flexibility and expandability
Faster modeling process than other modeling tools (e.g. TRNSYS)
Open-source → very large no. of available libraries from different domains (multi-domain modeling)

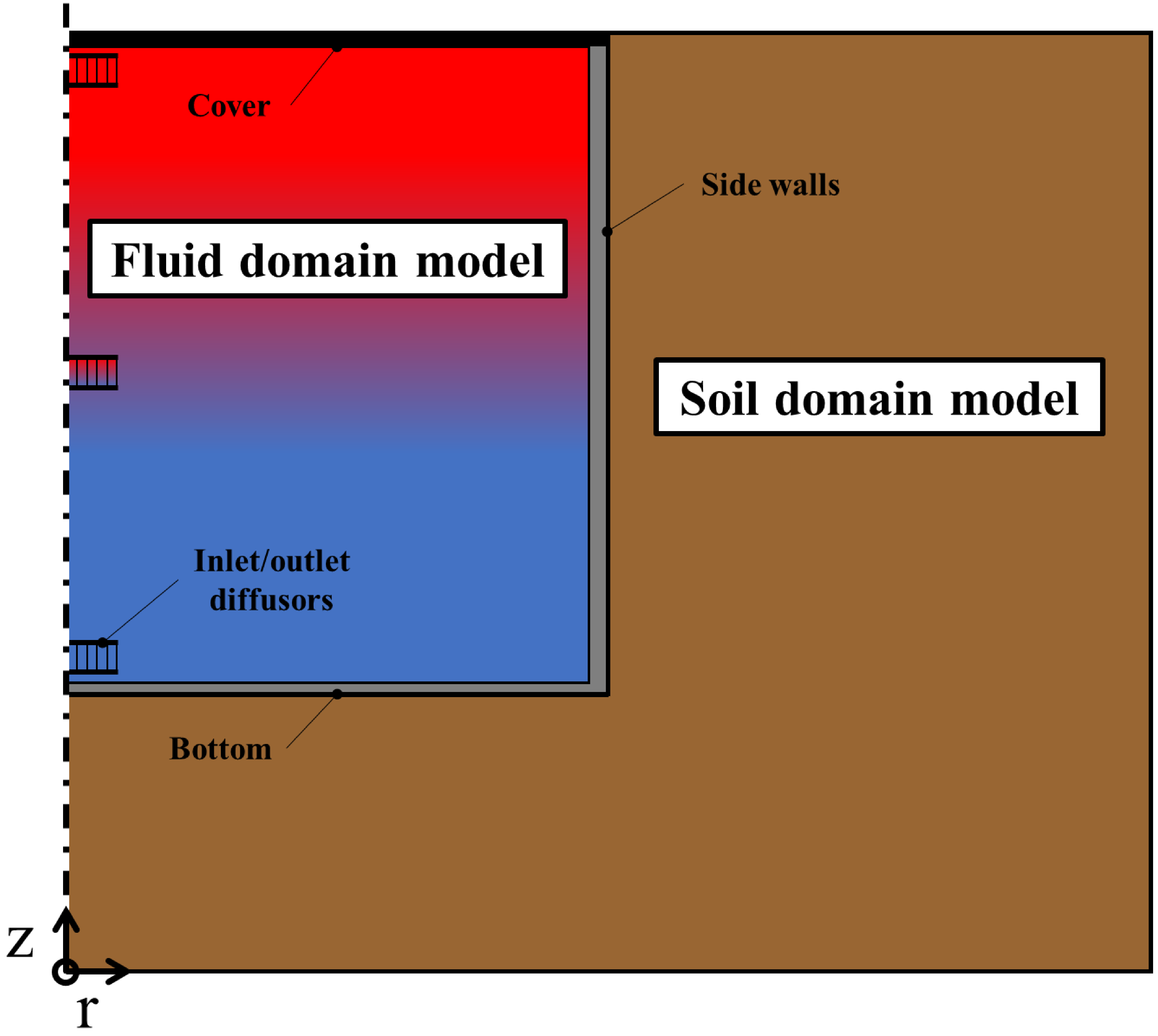
Why a new Modelica model? (Why no Co-simulation)?

To fully exploit the features of Modelica (e.g. flexibility, expandability,…)
Co-simulation may lead to [3]:

long implementation time,
poor computational performance and
loss of information.

[1] Pauschinger, T., Schmidt, T., Soerensen, P.A., Snijders, A., Djebbar, R., Boulter, R., and Thornton, J. (2020). Design Aspects for Large-Scale Aquifer and Pit Thermal Energy Storage for District Heating and Cooling. Final Project Report (IEA DHC/CHP Annex XII). Solites, Stuttgart (DE).
[2] Wetter, M., and van Treeck, C. (2017). New Generation Computing Tools for Building and Community Energy Systems. Final Project Report (IEA EBC Annex 60). Lawrence Berkeley National Laboratory, Berkeley (US) and RWTH Aachen University, Aachen (DE).
[3] Dahash, A., Ochs, F., and Tosatto, A. (2019). Co-Simulation of Dynamic Energy System Simulation and COMSOL Multiphysics®. Proceedings from COMSOL Conference 2019. Cambridge (UK), 24–26 September 2019.

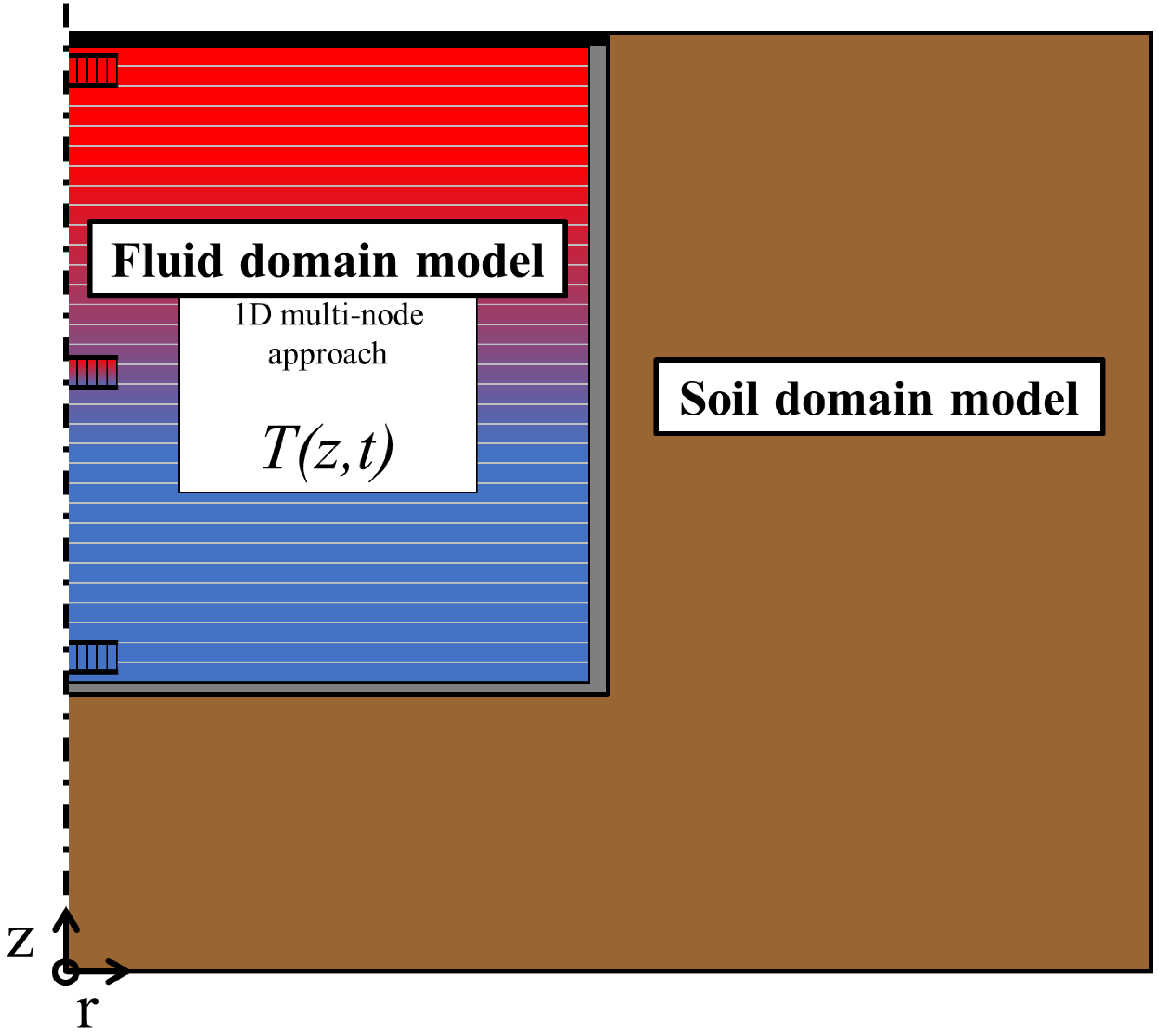
Model description: Overview



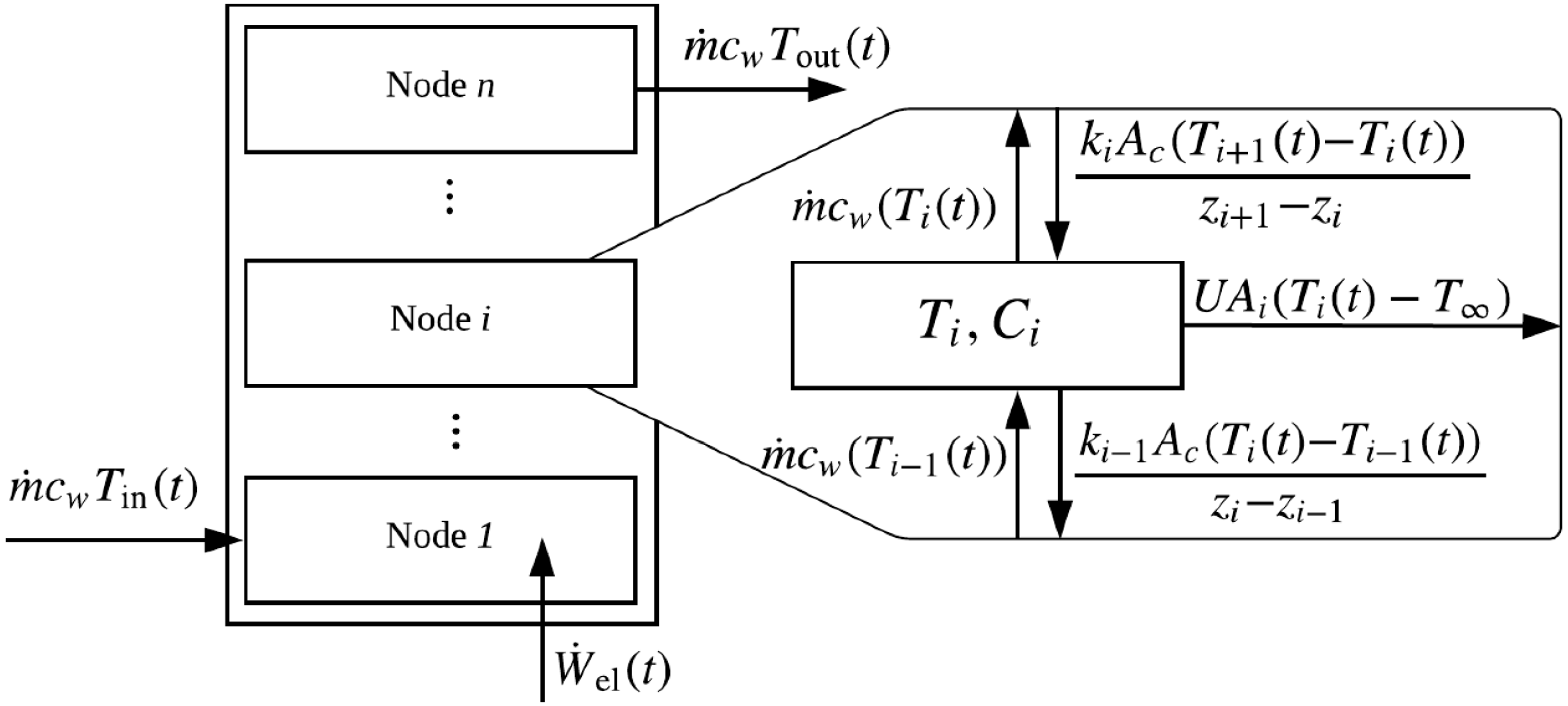
- Modelica model, developed and simulated within the modeling and simulation environment *Dymola* [4]
- Based on existing models from the *Modelica Standard library* [5] and the *Modelica Buildings library* [6], supplemented by several adaptions and extensions of these models
- Two main models: fluid domain model and soil domain model

[4] https://www.3ds.com/products-services/catia/products/dymola/
[5] Modelica Association. Modelica Standard Library (version 3.2.3). Modelica. Linköping, Sweden: Modelica Association, 2019. https://github.com/modelica/ModelicaStandardLibrary.
[6] Wetter, Michael, Wangda Zuo, Thierry S. Nouidui, and Xiufeng Pang. "Modelica Buildings Library." Journal of Building Performance Simulation 7, no. 4 (July 4, 2014): 253–70. https://doi.org/10.1080/19401493.2013.765506.

Model description: Fluid domain model



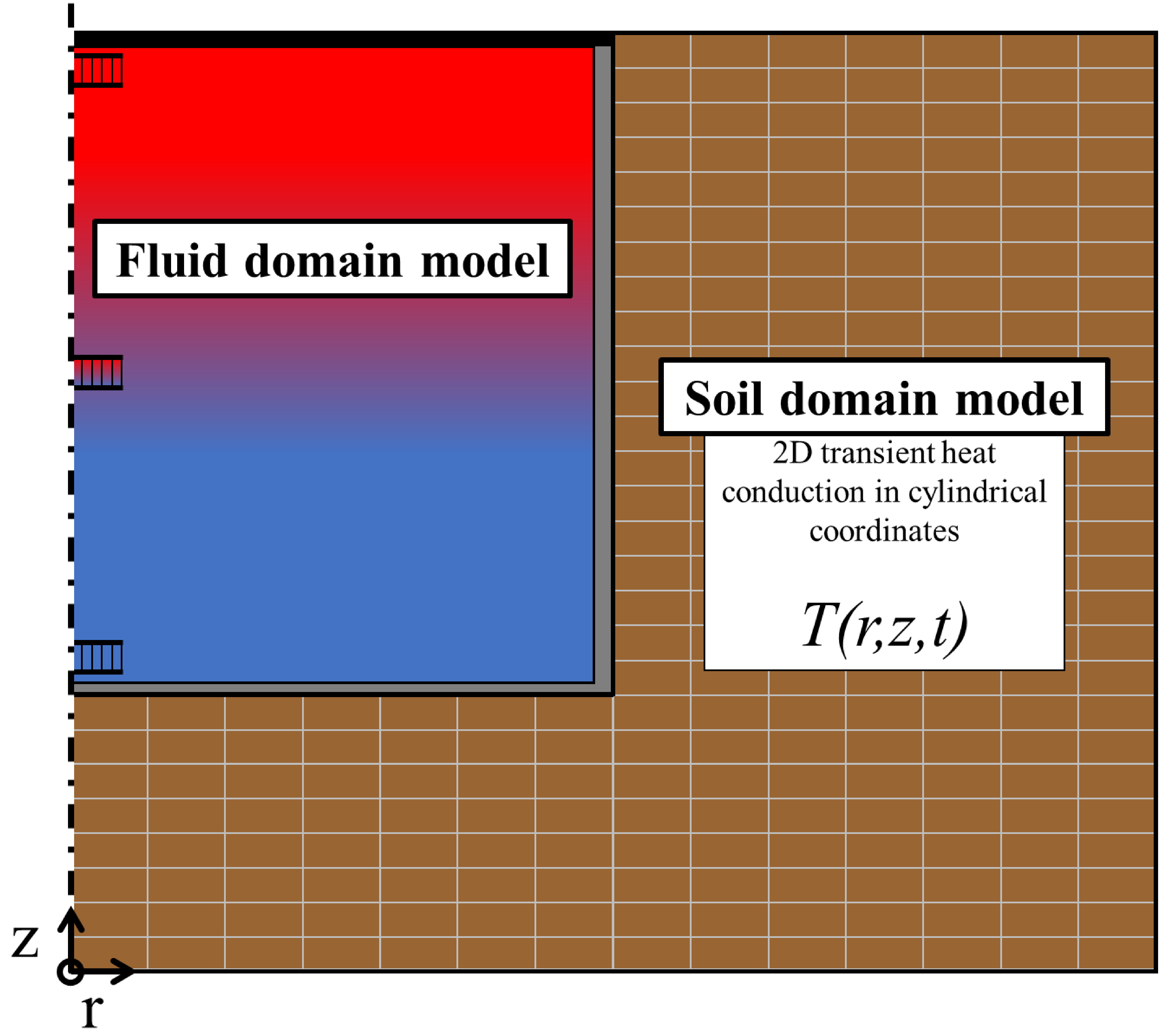
- Fluid domain model: 1D multi-node approach
  - Fluid domain is divided into finite-volumes (nodes) with a uniform horizontal temperature
  - Governing equations:



Governing equations of the 1D multi-node approach [7].

[7] Kepplinger, Peter. "Autonomous Demand Side Management of Domestic Hot Water Heaters," 2018. https://www.researchgate.net/publication/332834319_Autonomous_Demand_Side_Management_of_Domestic_Hot_Water_Heaters.

Model description: Soil domain model



- Governing differential equation:

Two-dimensional transient heat conduction in cylindrical coordinates with constant thermophysical properties [8]:

$$\frac{1}{\alpha}\frac{\partial T(r,z,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T(r,z,t)}{\partial r}\right) + \frac{\partial^2 T(r,z,t)}{\partial^2 z}$$

where $\alpha = k/(\rho \cdot c_p)$ is the thermal diffusivity of the soil with the thermal conductivity k, the density ρ and the specific heat capacity c_p. T is the temperature of the node at the time t, the radial location r and axial location z.

- The differential equation is solved using the finite difference method (FDM) and by proper discretization of the soil domain.

[8] Çengel, Yunus A., and Afshin J. Ghajar. Heat and Mass Transfer: Fundamentals & Applications. Fifth edition. New York, NY: McGraw Hill Education, 2015.

Validation case study: Description

Picture of the Dronninglund PTES during construction, before filling and installation of the liners and the cover [9].

- Presented model configuration was examined in a validation case study:
  - Comparison of the simulation results against measurement data of a real Danish PTES (in Dronninglund)
  - The Modelica model was evaluated as a stand-alone component and all other system components were excluded from the validation
  - Hourly temperature and mass flow rates at the corresponding inlet and outlet diffusers were used as input data for the simulation
  - Major model parameters (e.g. cylinder dimensions, U-values, diffuser heights) were adapted to the truncated pyramid geometry

[9] Sørensen, Per Alex, Christian Schmidt, Bjarke Lava Paaske, Lasse Kjærgaard, Carsten Møller Nielsen, and Thomas Schmidt. "Final Report - Sunstore 3 - Phase 2 - Implementation." EUDP 2009, March 2015.

Validation case study: Results (1)

Comparison between simulated and measured storage temperatures for the year 2015 in daily resolution; a) at the three inlet and outlet diffuser heights; and b) at the top, between top and middle and middle and bottom diffuser. R^2 values are presented in the corresponding colored boxes.

Validation case study: Results (2) and conclusion

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Comparison between measurement data and simulation results for the validation year 2015. Measurements derived from [10] and [11].

	Meas.	Sim.	Difference	
	[MWh]	[MWh]	[MWh]	[%]
Charged energy	12 761	12 635	-126	-1.0
Discharged energy	11 983	11 977	-6	0.0
Internal energy change	-497	-466	31	6.2
Total thermal losses	1 275	1 124	-151	-11.8
Top	788	827	39	4.9
Side	-	256	-	-
Bottom	-	42	-	-
Storage efficiency [%]	90.0	91.1	1.1	

[10] Dahash, Abdulrahman, Fabian Ochs, Alice Tosatto, and Wolfgang Streicher. “Toward Efficient Numerical Modeling and Analysis of Large-Scale Thermal Energy Storage for Renewable District Heating.” Applied Energy 279 (December 1, 2020): 115840. https://doi.org/10.1016/j.apenergy.2020.115840.

[11] Winterscheid, Carlo, and Thomas Schmidt. “Dronninglund District Heating Monitoring Data Evaluation for the Years 2015 - 2017.” Solites, May 31, 2019. https://www.solar-district-heating.eu/wp-content/uploads/2019/10/Dronninglund-evaluation-report-2015-2017_20190531.pdf.

- Conclusion of validation case study:
  - <u>The model provides satisfying results for the application in system simulations</u> → small deviations in charged & discharged energy and storage temperatures
  - Somewhat higher deviations in thermal losses (especially side and bottom thermal losses) → this has to be considered for detailed design studies
  - Possible reasons for the deviation in thermal losses:
    - Parameterization of the model
    - Deviations in the geometry

Further investigations and applications of the model (so far)

- Cross-comparison against other numerical models (TRNSYS and COMSOL Multiphysics) with same validation case study (PTES Dronninglund)

  → Good agreement with comparable models suited for system simulations (see [12])

- Comprehensive model comparison together with other LTES models of different simulation tools (COMSOL Multiphysics, TRNSYS and MATLAB/Simulink) in a generic case study

  → Good agreement between the developed model and all other models (see [13])

- Application of the model within the project giga_TES for system simulations, techno-economic analyses and parameter studies of several case studies of different locations and scenarios in Vienna and Salzburg (Austria)

  → Model showed a good compromise between computational performance and accuracy (see [14])

[12] Reisenbichler, Michael, Keith O'Donovan, Carles Ribas Tugores, Wim Van Helden, and Franz Wotawa. "Towards More Efficient Modeling and Simulation of Large-Scale Thermal Energy Storages in Future Local and District Energy Systems." In Proceedings of Building Simulation 2021: 17th Conference of IBPSA. Bruges, BE: International Building Performance Simulation Association, 2021.

[13] Ochs, Fabian, Abdulrahman Dahash, Alice Tosatto, Michael Reisenbichler, Keith O'Donovan, Geoffroy Gauthier, Christian Kok Skov, and Thomas Schmidt. "Comprehensive Comparison of Different Models for Large-Scale Thermal Energy Storage [Manuscript Submitted for Publication]." In Proceedings of the 14th International Renewable Energy Storage Conference 2021 (IRES 2021). Düsseldorf, DE: Atlantis Press, 2021.

[14] https://www.gigates.at/index.php/en/

Conclusion and outlook

Conclusion

1. Hot-water underground LTES can massively increase the proportion of renewable energy in future local and district energy systems.
2. To fully exploit the potential, comprehensive planning and tuning of the overall system by dynamic system simulations is necessary.
3. Modelica-based simulation tools show many advantages over other established tools.
4. Consequently, a novel Modelica LTES model was developed.
5. The validation case study and further investigations showed an adequate accuracy and a good usability of the model for system simulations.

Outlook

- Extension of the storage model to conical geometries is in progress

  → Preliminary results of the validation case study and the cross-comparison with other numerical models show promising results (*should hopefully be published in another paper soon*)

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