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MODULAR 1D STRATIFIED THERMAL ENERGY STORAGE MODEL WITH MULTI-PORT INTERFACE FOR DISTRICT HEATING CO-SIMULATION: DESIGN AND VALIDATION

Summary

A modular, open-source 1D finite-volume model for stratified thermal energy storage is presented, designed for co-simulation with district heating network solvers. Its multi-port hydraulic interface supports an arbitrary number of diffusors at user-defined heights, enabling realistic representation of heat pumps, solar collectors, and network connections operating simultaneously. Benchmarking against FreeTTES (Narusavicius et al., 2024), a Lagrangian segment model used as numerical reference, shows outlet temperature errors of 0.47–1.20 K across three scenarios at 0.16–0.19 ms per timestep, well within the budget of district heating co-simulation timesteps. Validation against the full calendar year 2024 of the Høje Taastrup pit thermal energy storage (70 880 m^3, Denmark) yields MAE of 2.13 K and 1.59 K at the network-relevant outlet positions without parameter calibration. Network coupling via FMI as well as fine-tuning of model parameters and further validation with additional datasets is the subject of ongoing work.

Keywords: seasonal thermal energy storage, thermal stratification, pit thermal energy storage, district heating, co-simulation, finite volume method, multi-port interface, FMI

Field of application: Solar district heating, seasonal thermal energy storage, district energy system simulation

Addressed audience: Simulation engineers, district heating planners, solar thermal researchers

1. Introduction

Stratified thermal energy storage is a key component in district heating systems, yet its representation in network co-solvers typically relies on simplified models with fixed geometry and a two-port hydraulic interface that cannot capture real pit or tank thermal energy storages (PTES / TTES) with multiple simultaneous diffusor connections, heat pump loops, and solar collector circuits (Boß et al., 2024; Xiang et al., 2022). More detailed Lagrangian segment models achieve higher accuracy but are approximately three orders of magnitude slower (Narusavicius et al., 2024), limiting their usability as inline co-simulation components. This paper presents a modular, open-source 1D finite-volume (FV) model that addresses both gaps: a general multi-port hydraulic interface supports arbitrary diffusor configurations, and independently exchangeable sub-models for geometry, heat loss, and fluid properties allow direct application to cylindrical buffer tanks and trapezoidal PTES, both in the 50 000–70 000 m^3 range, without code modifications.

2. Model

The central design feature is a port-based hydraulic API: each timestep receives n ports defined by height z_k, signed mass flow $\dot{m}_k$, and inlet temperature $T_{k,\text{in}}$; mass balance is enforced internally. Any combination of simultaneous charging, discharging, and recirculation is supported, enabling direct representation of PTES diffusor systems, heat pump return connections, and solar collector loops without code modifications. This interface is the intended attachment point for FMI network coupling (ongoing work).

Physical sub-models are independently exchangeable (Tab. 1). The standard 1D FV energy balance (Lago et al., 2019; Untrau et al., 2023) is solved with either explicit Euler + TVD advection (van Leer limiter) or implicit Euler + upwind advection (TDMA), the latter being unconditionally stable and preferred for co-simulation timesteps of 900–3600 s; at these timesteps both advection schemes produce equivalent results. Inverted stratification is corrected by caloric mass-weighted mixing after each step (Xiang et al., 2022).

Tab. 1: Exchangeable model components.

Component	Available implementations
Geometry	Cylinder, truncated cone, truncated pyramid
Heat loss	Constant ambient, split lid/wall, depth-dependent ground
Fluid props.	Temperature-dependent polynomial fits (water)
Diffusors	n ports at arbitrary heights (multi-port API)

3. Results

3.1 Numerical benchmark

The model is benchmarked on a representative large cylindrical tank ($V = 50\,140\,\mathrm{m}^3$, $H = 39.9\,\mathrm{m}$) against a Lagrangian reference (Narusavicius et al., 2024) across three scenarios: a standard 60 h charge/standby/discharge cycle, a rapid 8 h alternating cycle, and a full annual seasonal simulation (8 760 h). Selected results are shown in Tab. 2.

The implicit solver with $N = 50$ nodes achieves 0.47–1.20 K MAE relative to this reference across scenarios, at 0.16–0.19 ms per timestep (Intel Core i7-13620H, single-threaded Python), which is well within the budget of typical co-simulation timesteps of 900–3 600 s. A fully-mixed 0D model deviates by 16–18 K in weekly cycling, confirming that stratification modelling is essential for dynamic supply temperature prediction; at the annual timescale its mean temperature error reduces to <2 K (Tab. 2). Increasing to $N = 200$ nodes reduces MAE by only 0.04–0.05 K (0.43 K weekly, 1.16 K annual) at 2.5× the computation time (0.41–0.47 ms/step), indicating that results are grid-converged at $N = 50$. The explicit TVD counterpart ($N = 50$) achieves comparable accuracy (0.58 K weekly, 1.13 K annual) but requires CFL-driven substepping at $\Delta t = 3\,600\,\mathrm{s}$, increasing annual computation time by 38 %; the implicit solver is therefore the default for co-simulation timesteps.

Tab. 2: Benchmark results: MAE and computation time ($\Delta t = 3600\,\mathrm{s}$, i7-13620H). 0D = lower-complexity baseline; Lagrangian = accuracy reference.

Scenario	Configuration	MAE [K]	ms/step
Weekly	0D fully mixed	16.3	<0.01
	N50 implicit upwind	0.47	0.19
Annual	0D fully mixed	1.94	<0.01
	N50 implicit upwind	1.20	0.16
Accuracy ref.	Lagrangian (FreeTTES)	(ref.)	447

3.2 Validation against Høje Taastrup PTES (2024)

The multi-port interface is applied to the Høje Taastrup PTES, the pit storage of a large solar district heating plant (Denmark; $V \approx 70\,880\,\mathrm{m}^3$, bottom 29.4 × 29.4 m, top 105.4 × 105.4 m, $H = 14.05\,\mathrm{m}$; Sifnaios et al., 2025). Three ports are placed at the measured diffusor heights (13.80 m, 10.50 m, 0.45 m above floor); ten-minute mass-flow boundary conditions, inlet temperatures, and outdoor air temperature are taken directly from the dataset. The simulation covers the full year 2024 (52 704 steps at $\Delta t = 600\,\mathrm{s}$), initialised from the measured temperature profile on 1 January. Heat-loss coefficients for lid ($U_{\mathrm{lid}} = 0.151\,\mathrm{W\,m^{-2}K^{-1}}$) and walls/floor ($U_{\mathrm{wall}} = 0.30\,\mathrm{W\,m^{-2}K^{-1}}$) are estimated from the physical construction and soil properties reported by Sifnaios et al. (2025), without parameter calibration; in-storage lance sensors are used as measurement reference (pipe sensors cool to ambient during standby).

Fig. 1 shows simulated vs. measured lance temperatures at the top and bottom positions. MAE at these network-relevant outlet positions is 2.13 K and 1.59 K (no parameter calibration; sensor accuracy ±0.2 K, Sifnaios et al., 2025); the middle position (10.50 m) shows 3.22 K, reflecting thermocline position uncertainty during seasonal transitions, a known limitation of the 1D plug-flow model class (Xiang et al., 2022). The full-year simulation ($N = 50$, implicit) completes in 3.2 s.

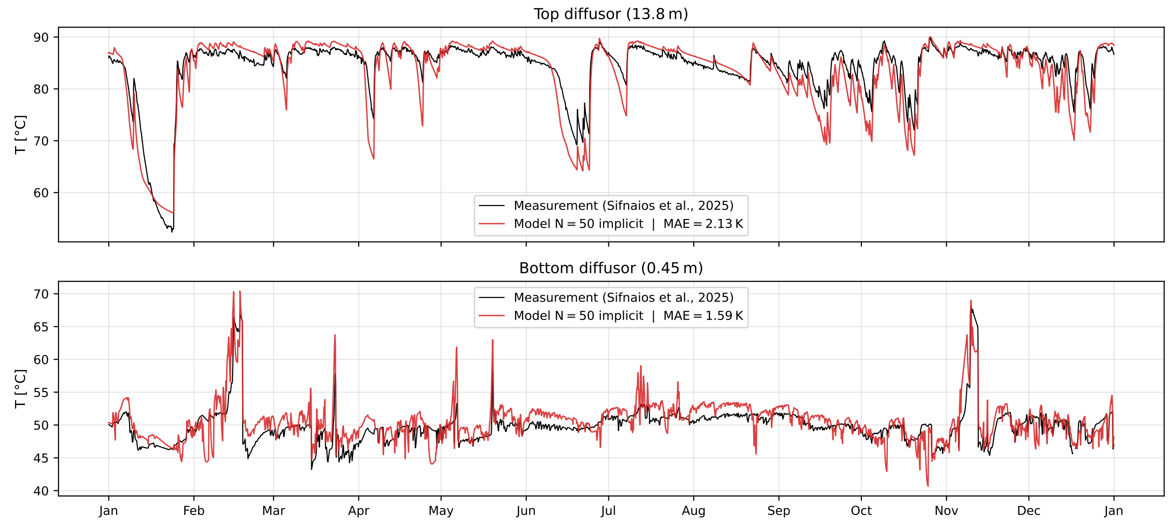

Fig. 1: Høje Taastrup PTES 2024: simulated (red) vs. measured (black) lance temperatures at top (13.80 m) and bottom (0.45 m) diffusor. Full-year simulation, no parameter calibration.

4. Conclusions

A modular, open-source 1D FV model for stratified TES with a general multi-port interface has been presented. Using a Lagrangian model as numerical reference, the implicit solver ($N = 50$) achieves 0.47–1.20 K MAE at 0.16–0.19 ms per timestep, well within co-simulation budgets. Validation against the Høje Taastrup PTES (Sifnaios et al., 2025) yields 2.13 K and 1.59 K MAE at the network-relevant outlet positions over the full year 2024 without calibration; remaining errors at the middle diffusor are attributed to thermocline position uncertainty, a known 1D plug-flow limitation (Xiang et al., 2022). The multi-port interface is designed as the natural attachment point for FMI network coupling; co-simulation validation and parameter calibration remain the subject of future work.

5. References

Boß, V., Felsmann, C., Narusavicius, B., Rühling, K., 2024. Planning Tools for Decentralized Heat Supply: Modeling the Effects of Volatile Renewable Energies. *Proc. ISEC 2024*. doi:10.52825/isec.v1i.1110

Lago, J., Ridder, F., Schutter, B., Helsen, L., 2019. A 1-dimensional continuous and smooth model for thermally stratified storage tanks including mixing and buoyancy. *Applied Energy* 248, 640–655.

Narusavicius, B., Koch, F., Matthees, A., Stange, P., Rühling, K., 2024. Prediction of the Temperature Field Development in Large Heat Storage Tanks for Integration in Network Simulation. *34. Symp. Solarthermie und Innovative Wärmesysteme, Proc. 1*. doi:10.52825/st-symposium.v1i.1350

Sifnaios, I., Furbo, S., Jensen, A.R., 2025. Monitoring data of the Høje Taastrup water pit thermal energy storage. *Data in Brief* 59, 111380. doi:10.1016/j.dib.2025.111380

Untrau, A., Sochard, S., Marias, F., Reneaume, J.-M., Le Roux, G.A.C., Serra, S., 2023. A fast and accurate 1-dimensional model for dynamic simulation and optimization of a stratified thermal energy storage. *Applied Energy* 333, 120614.

Xiang, Y., Xie, Z., Furbo, S., Wang, D., Gao, M., Fan, J., 2022. A comprehensive review on pit thermal energy storage: Technical elements, numerical approaches and recent applications. *Journal of Energy Storage* 55, 105716.