

Geometric Optimization of Latent Heat Thermal Energy Storage for Carnot Batteries based on Multiscale Simulation

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1. Motivation & Objective

- Latent Heat Thermal Energy Storages (LHTES) enable highly efficient and energy-dense Carnot Batteries
- Heat is charged and discharged via a heat transfer fluid flowing through vertical finned tubes
- Problem 1: Current design models are **computationally expensive**
- Problem 2: Lack of a systematic method to **maximize heat transfer rates using minimal fin material**

Objective: To develop a quasi-analytical model of heat transfer in PCM storages suitable for complex fin geometries

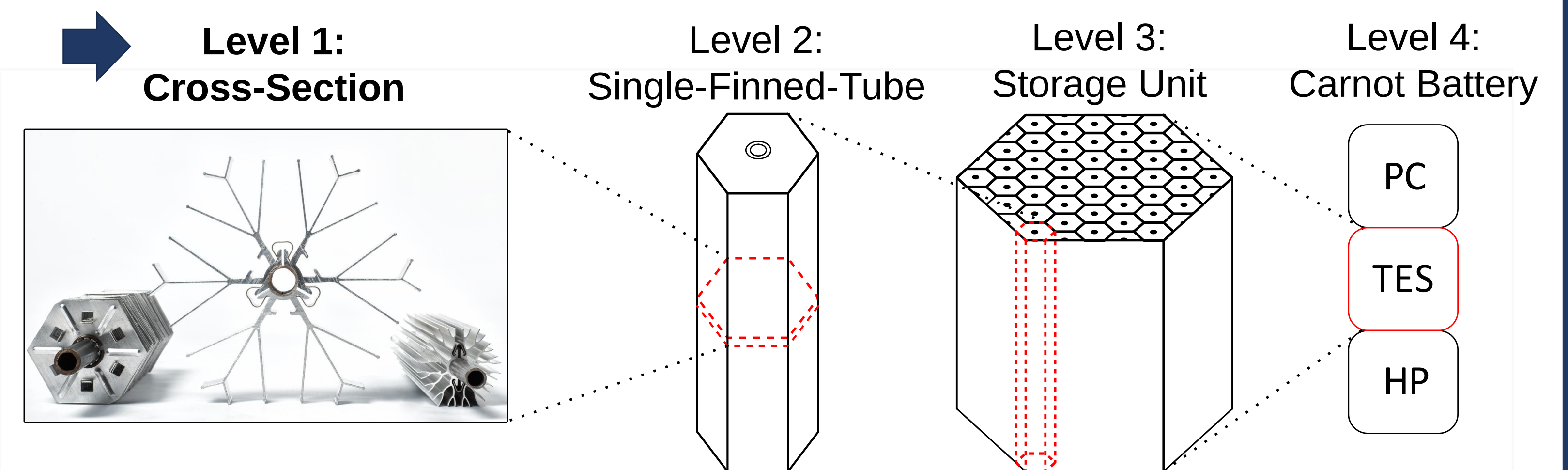


Fig. 1: Multiscale discretization of the LHTES Unit.

2. Methodology

Governing equations:

- Reference model: COMSOL

$$\rho c_{p,eff} \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T)$$

- Quasi-Analytical Solution (AS) python

$$t = \frac{\rho_{PCM} L_m}{\Delta T} \left(s \cdot R_{fin} + \frac{s^2}{2 k_{PCM}} \right); \dot{q} = \frac{\Delta T}{R_{fin} + \frac{s}{k_{PCM}}}$$

*We consider $s = D_{PCM-fin}$, with s : position of the PC front

- Cumulative Distribution Function

$$CDF(d) = \frac{1}{N} \sum H(d - D_i)$$

- Effective thermal conductivity boundaries (fit):

$$k_{parallel} = f_{fin} k_{fin} + (1 - f_{fin}) k_{PCM}$$

$$k_{series} = \left(\frac{f_{fin}}{k_{fin}} + \frac{1 - f_{fin}}{k_{PCM}} \right)^{-1}$$

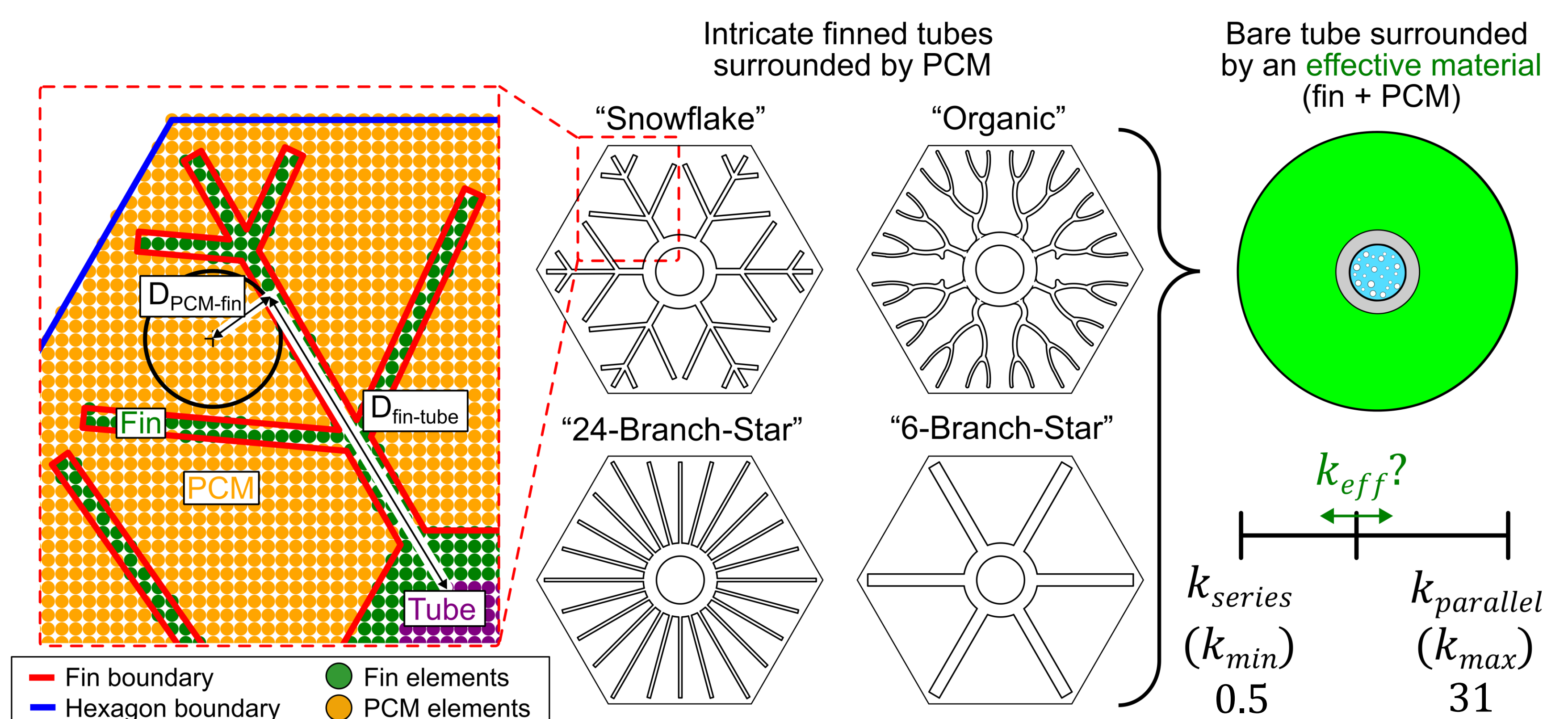


Fig. 2: Heat transfer paths concept [1], studied fin profiles, and effective material.

3. Results

Table 1: Fin profile comparison.

Fin profile	24-Branch-Star	Organic	Snowflake	6-Branch-Star
t_{pc}	1130 s (18 min)	1355 s (22 min)	1885 s (31 min)	5785 (96 min)
$k_{eff} [W m^{-1} K^{-1}]$	27.1	20.2	13.7	4.1
$t_{CT,COMSOL}$	732 s (12 min)	2141 s (35 min)	1551 s (25 min)	1167 s (19 min)
$t_{CT,AS}$	5.0 s	5.5 s	4.9 s	4.8 s
R_{speed}	146	389	316	243

t_{pc} : Phase change time

k_{eff} : Effective thermal conductivity

$t_{CT,COMSOL}$: Computational Time of COMSOL

$t_{CT,AS}$: Comp. Time of the Analytical Sol.

R_{speed} : Comp. speedup ratio

$R_{speed} = t_{CT,COMSOL} / t_{CT,AS}$

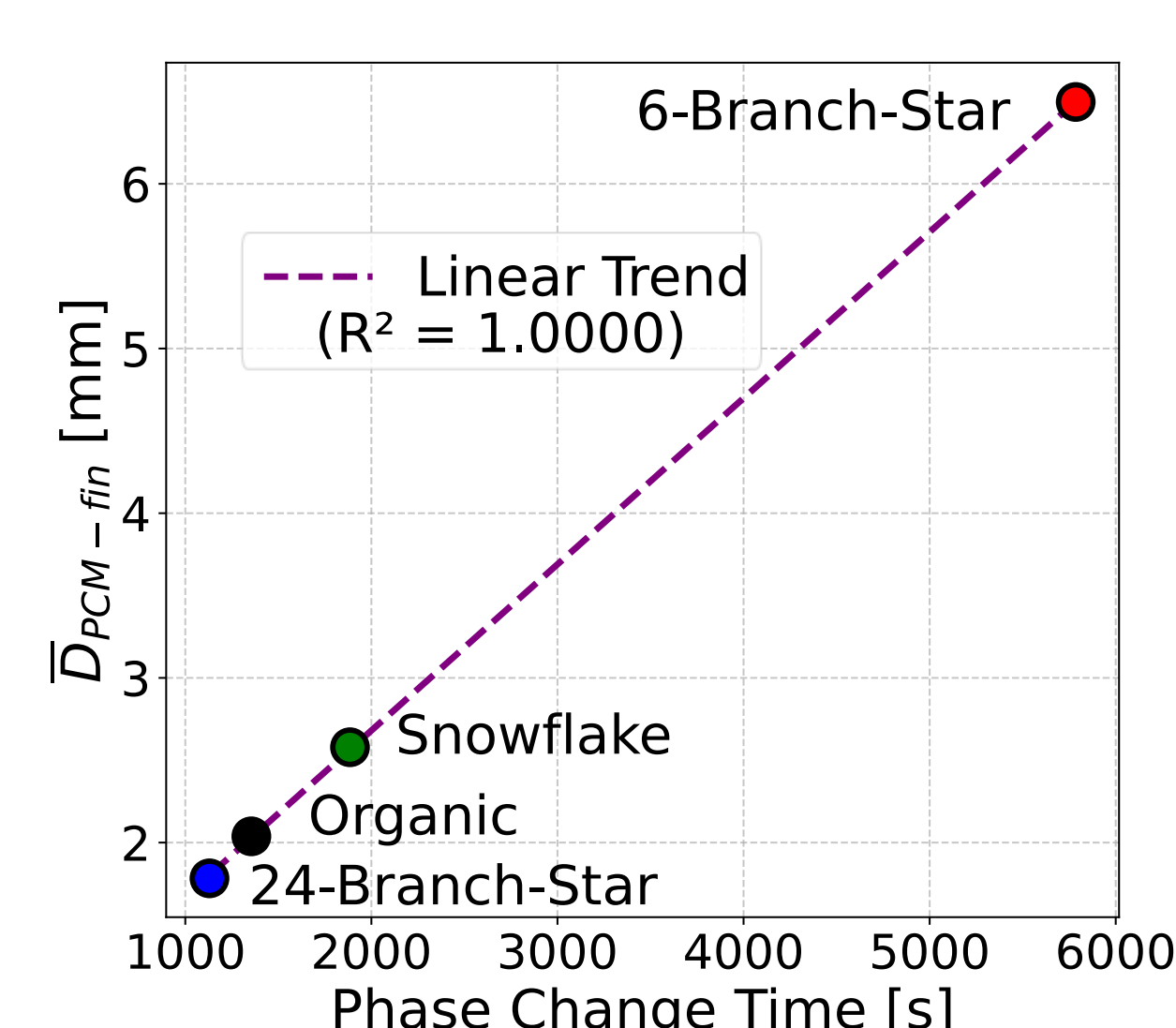


Fig. 3: Direct correlation between the average $D_{PCM-fin}$ and the phase change time [1].

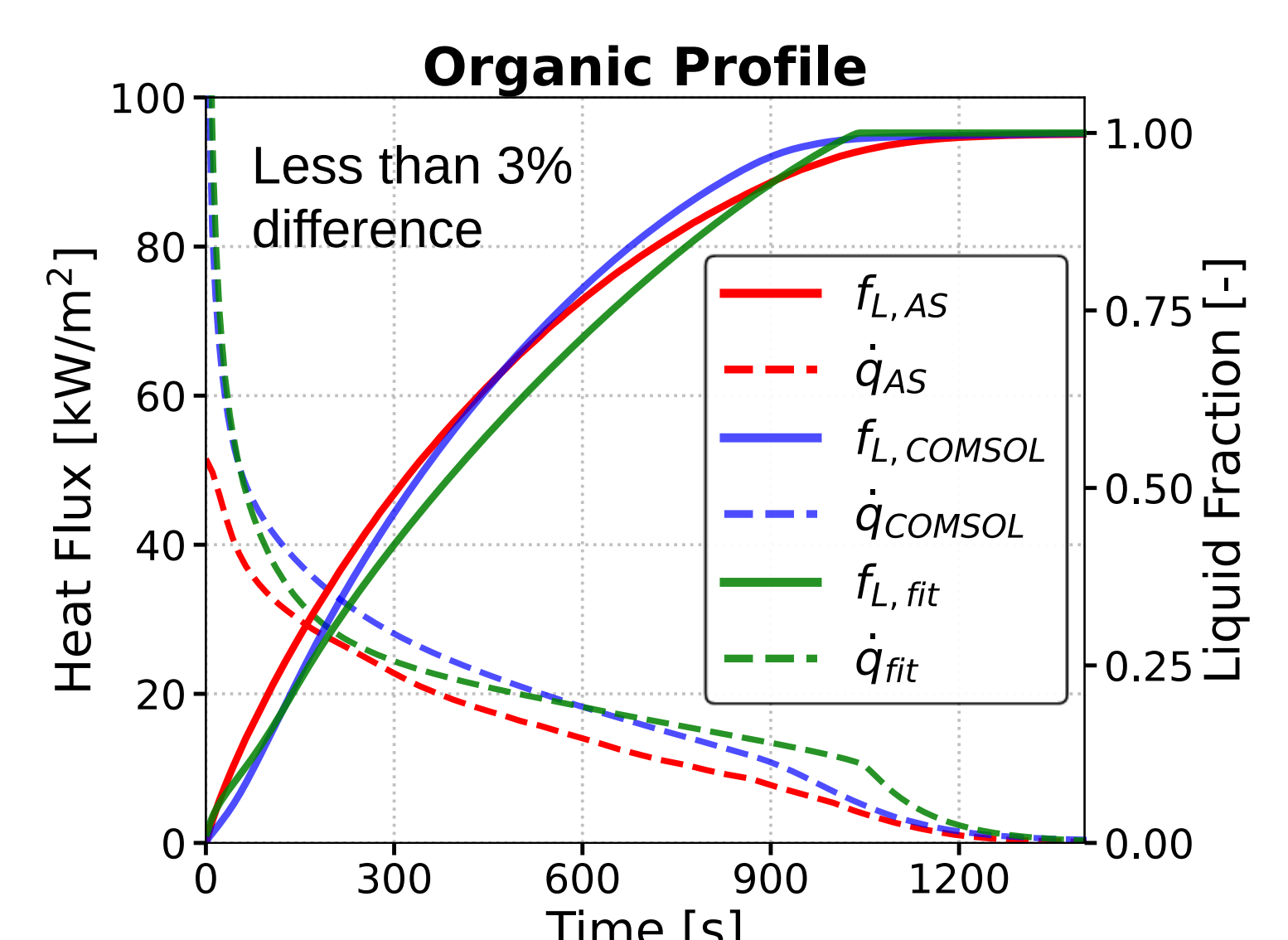


Fig. 4: Comparison of the reference COMSOL model, quasi-analytical model, effective conductivity model.

4. Conclusions & Outlook

- The heat transfer path is identified as a universal fin descriptor
- The first quasi-analytical model for the heat transfer of PCM storages with complex fin geometries was successfully derived and validated
- The developed model is up to **300 times faster than FEM analysis!**

→ **Next Step:** Fin optimization balancing heat transfer paths, manufacturing limitations, and industrial thermal demand

[1] Pezo et al. "New method for fast heat transfer analysis of PCM cross sections with integrated finned tubes", Applied Thermal Engineering, 305 (2026).

Paper [1]

