Wall impact on efficiency of packed-bed thermocline thermal energy storage system

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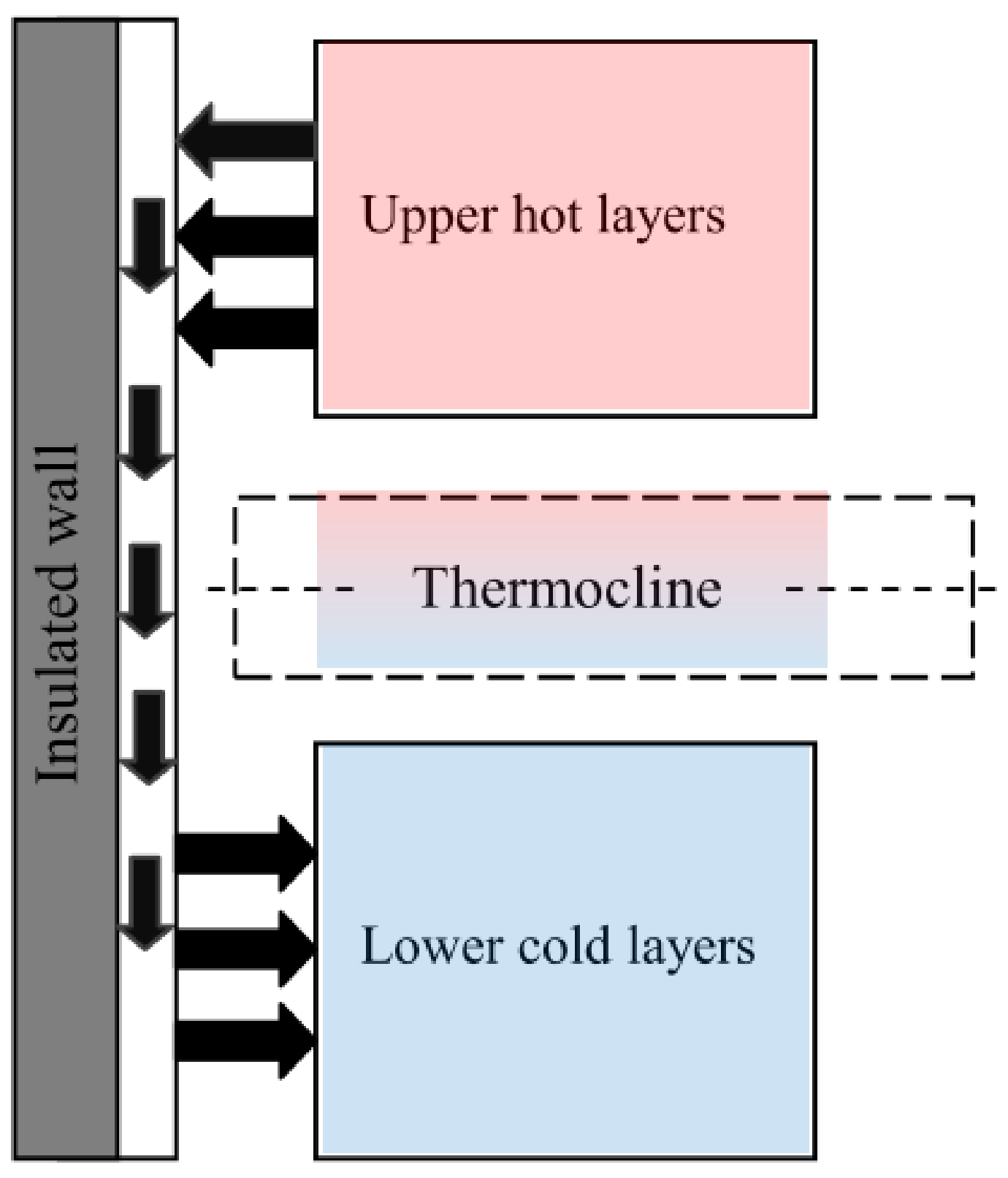
1. Introduction

Packed-bed single-tank thermal energy storage (TES) is a **low-cost alternative** to the conventional two-tank system for concentrated solar power (CSP) plant, which using cheaper solids as heat storage medium in direct contact with the heat transfer fluid to convey heat. In single tank, hot and cold fluid are separated by buoyancy force due to the different densities, forming a thermal gradient zone called "**thermocline**". As an indicator of thermal performance of the TES system, thermocline thickness can be effected by **wall heat capacity** through inducing fluid temperature inhomogeneity. Thus, it's necessary to comprehend the wall impact on thermal performance of packed-bed TES system for **improvement of system efficiency**.



Problem:

- Wall heat capacity spread the thermocline?

Method:

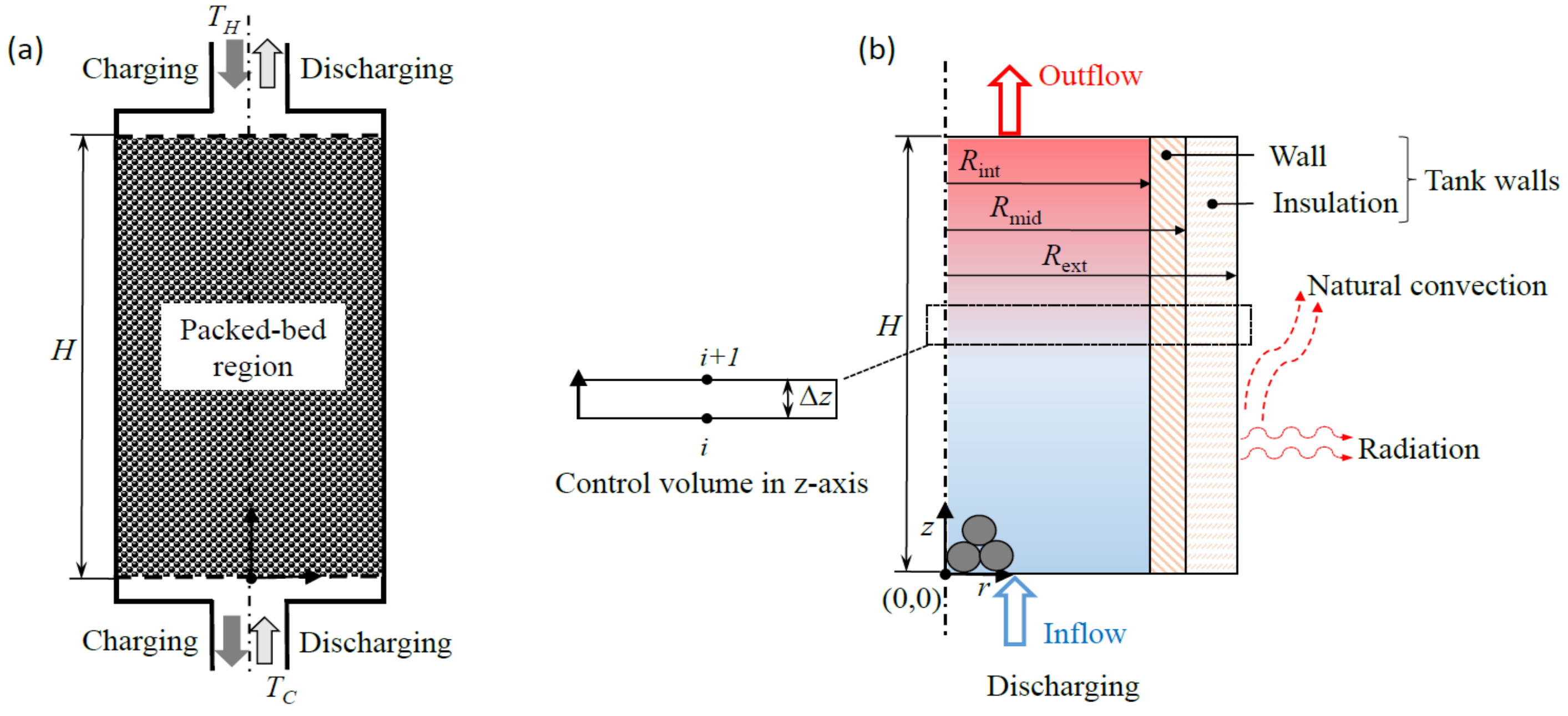
- Numerical simulation
- Validation with experimental data
- Wall impact (energy, thermocline…)

Model **1**: 1D-2P
Model **2**: 1D-3P
Model **3**: 1.5P-4P

2. Methodology

Geometry

► Computational domain of control volume of packed-bed TES tank in discharging.



Parameters	Units	Sandia lab pilot-scale tank	Hypothetical lab-scale tank
HTF	--	Molten salt	Water
Solid filler	--	Quartzite rock and sand	Quartzite rock and sand
Tank height (*H*)	m	6.0	0.4
Tank radius (R_{mid})	m	1.5	0.11
T_H/T_C	℃	390/290	75/20

Models

► Energy equations

Model 1:

$$\varepsilon \cdot \rho_f \cdot C_{p,f} \cdot \left(\frac{\partial T_f}{\partial t} + u_f \cdot \frac{\partial T_f}{\partial z}\right) = \frac{\partial}{\partial z} \cdot \left(\lambda_{f,eff} \cdot \frac{\partial T_f}{\partial z}\right) + h_{sf,eff} \cdot a_s \cdot (T_s - T_f) + h_o \cdot a_b \cdot (T_{amb} - T_f)$$

$$(1-\varepsilon) \cdot \rho_s \cdot C_{p_s} \cdot \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z} \cdot \left(\lambda_{s,eff} \cdot \frac{\partial T_s}{\partial z}\right) + h_{sf,eff} \cdot a_s \cdot (T_f - T_s)$$

Model 3:

$$\varepsilon \cdot \rho_f \cdot C_{p,f} \cdot \left(\frac{\partial T_f}{\partial t} + u_f \cdot \frac{\partial T_f}{\partial z}\right) = \frac{\partial}{\partial z} \cdot \left(\lambda_{f,eff} \cdot \frac{\partial T_f}{\partial z}\right) + h_{sf,eff} \cdot a_s \cdot (T_s - T_f) + h_{int} \cdot a_b \cdot (T_{w,int} - T_f)$$

$$\rho_{ins} \cdot C_{p,ins} \cdot \frac{\partial T_{ins}}{\partial t} = \frac{\partial}{\partial z} \cdot \left(\lambda_{ins} \cdot \frac{\partial T_{ins}}{\partial z}\right) + \frac{\lambda_{ins}}{r} \cdot \frac{\partial}{\partial r} \cdot \left(r \cdot \frac{\partial T_{ins}}{\partial r}\right)$$

$$(1-\varepsilon) \cdot \rho_s \cdot C_{p,s} \cdot \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z} \cdot \left(\lambda_{s,eff} \cdot \frac{\partial T_s}{\partial z}\right) + h_{sf,eff} \cdot a_s \cdot (T_f - T_s)$$

$$\rho_{ins} \cdot C_{p,ins} \cdot \frac{\partial T_{ins}}{\partial t} = \frac{\partial}{\partial z} \cdot \left(\lambda_{ins} \cdot \frac{\partial T_{ins}}{\partial z}\right) + \frac{\lambda_{ins}}{r} \cdot \frac{\partial}{\partial r} \cdot \left(r \cdot \frac{\partial T_{ins}}{\partial r}\right)$$

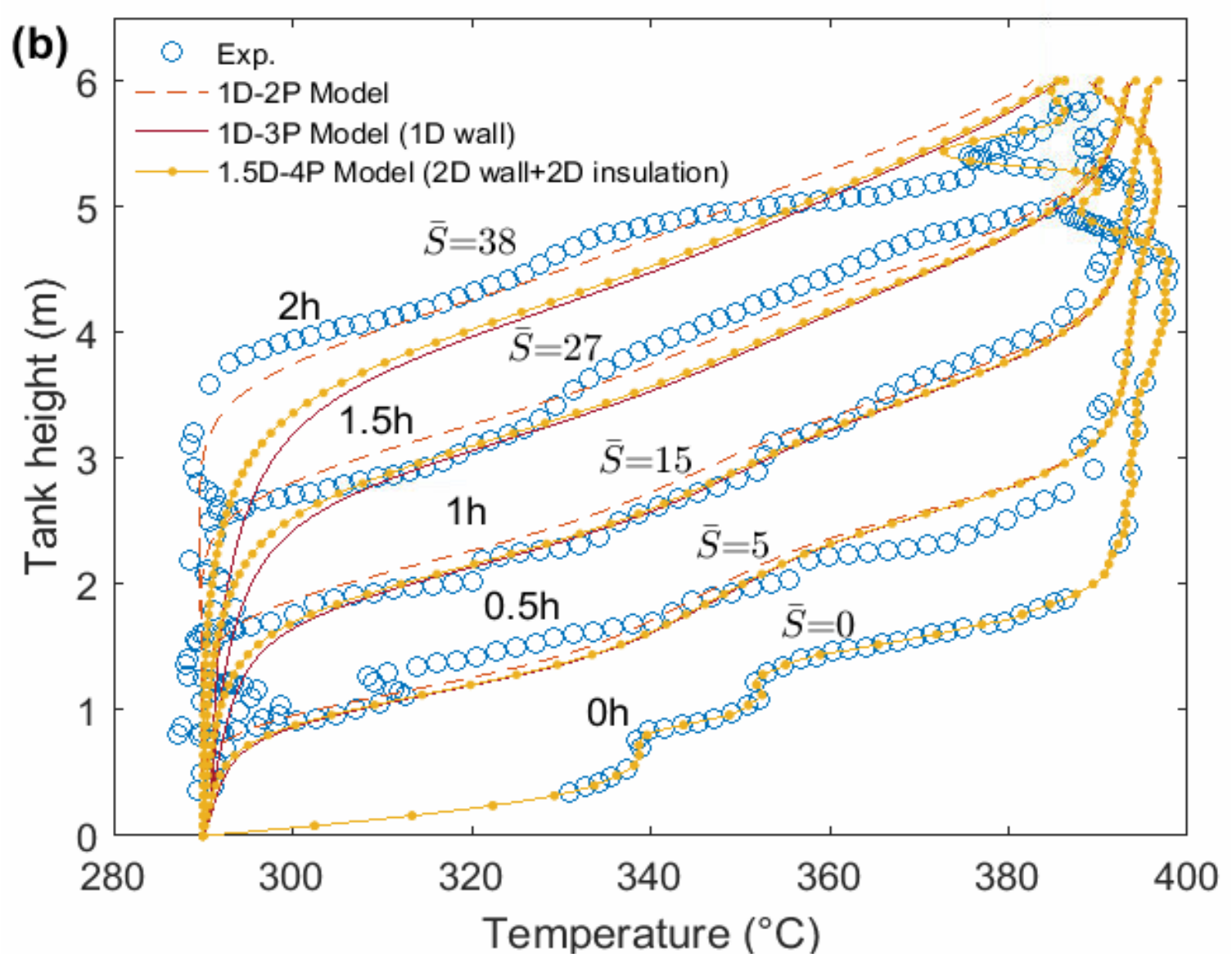
Validation and comparison of models

Computation time (s)			
Models	1D-2P	1D-3P	1.5D-4P
Pilot-scale tank	5	8	833
Lab-scale tank	9	10	606

► Validation with measured data from a 2.3 MWh_t Sandia lab pilot-scale tank.

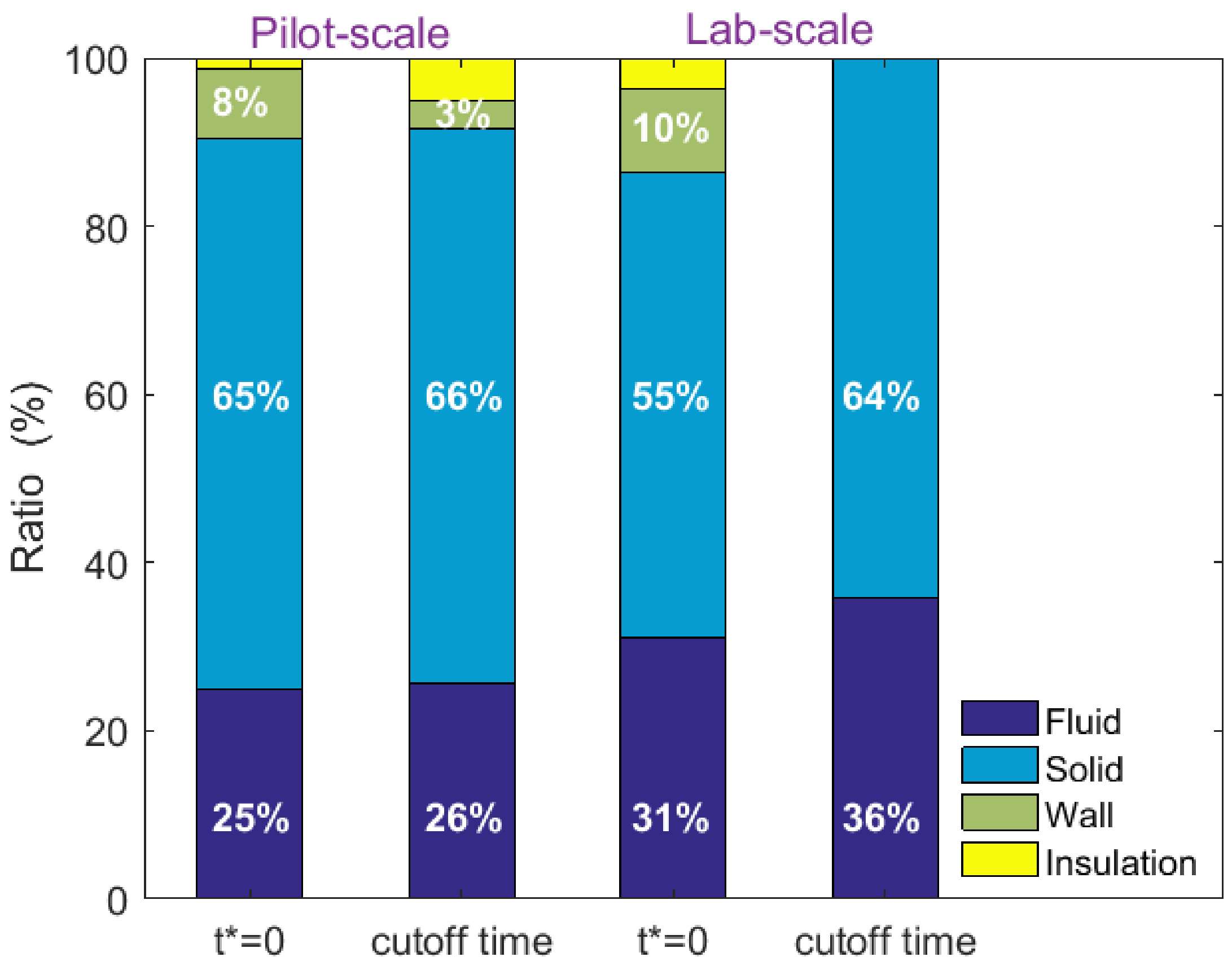
► Standard deviation:

$$std = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(T_{exp.} - T_{num.})^2}$$



3. Results and Discussion

- **Energy (*E*) ratio** **before and after discharging in two tank**

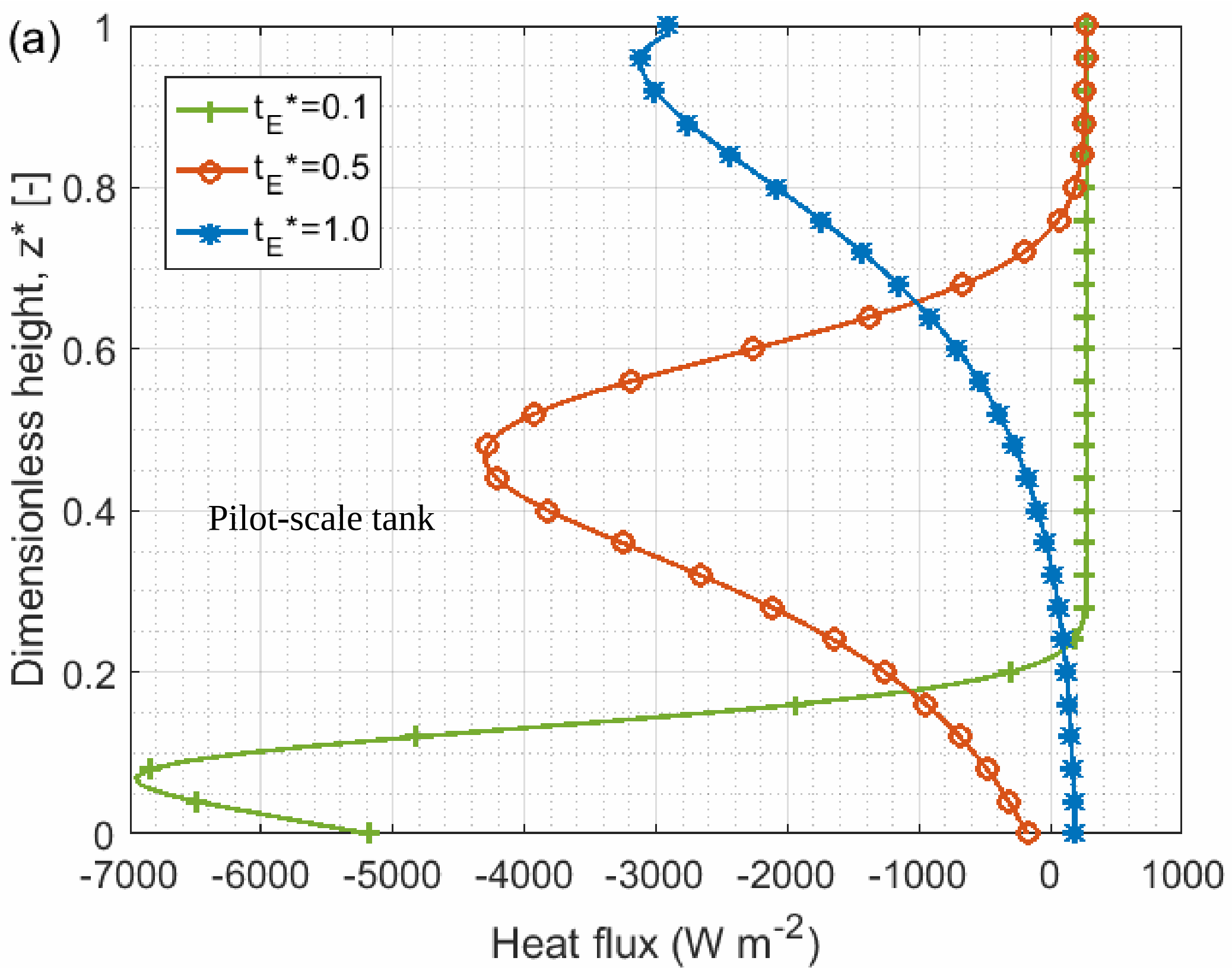


►The maximum **energy stored in the wall** before discharging can **up to 8%** of the total system;

►After discharging, the **energy** in the **wall and insulation** all **decrease** for two tanks, which means heat transfer to fluid or ambient.

$$E_{stored} = E_{f,stored} + E_{s,stored} + E_{w,stored} + E_{ins,stored}$$

- **Wall heat flux** **variation over time in discharging**



► **Heat flux peak** height and span increase over discharging time, reflects an increment of thermocline thickness since **wall heat transfer from wall to fluid** in discharging.

$$t_E^* = t \cdot \frac{\dot{m}_f \cdot C_p \cdot (T_H - T_C)}{E_{stored}}$$

Conclusion

- Energy stored in wall before discharging reaches up to 8% of total system energy, that can not be ignored.
- Wall heat capacity can cause **thermocline degradation** in discharging process.

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