Numerical study on the design parameters of a packed bed thermal energy storage system

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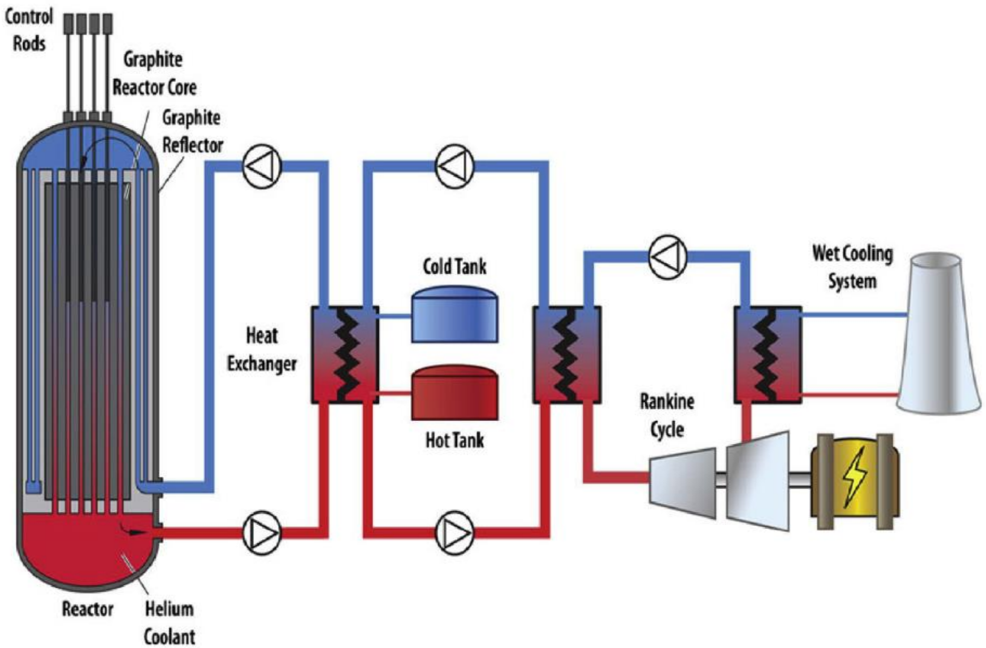
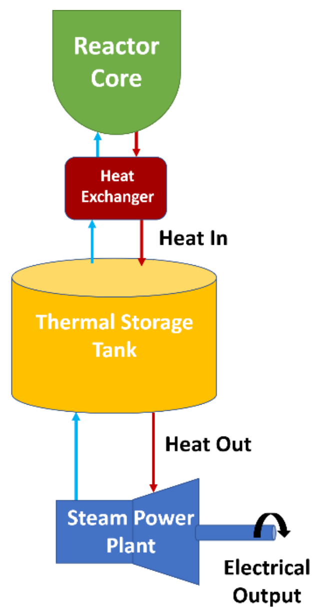
Introduction

- Renewable energy generation rate ↑, intermittency issue arises
- Thermal energy storage (TES) can be a key solution for grid stability problem
- TES is considered for flexible operation of NPPs



Conceptual NPP with TES system [Alva et al., 2018]



General Schematic of TES-Nuclear combined system

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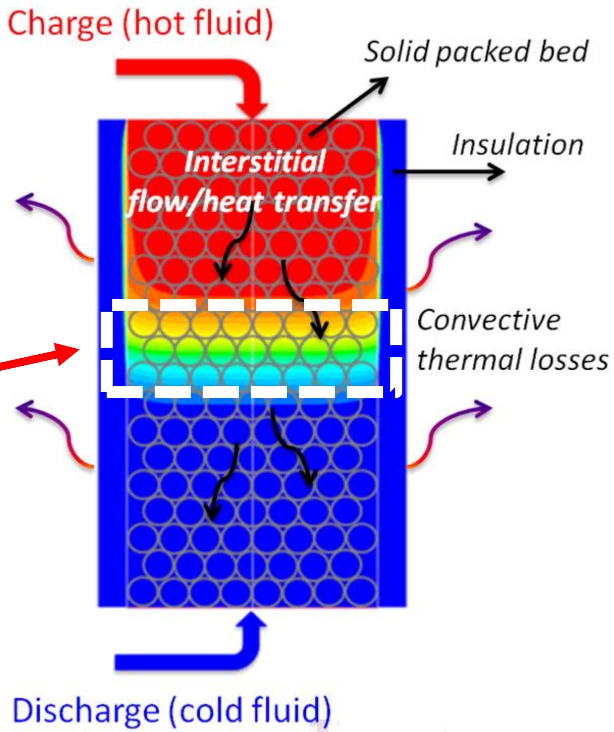
TES system using packed bed

- Thermocline thermal energy storage (TES)
  - ✓ Charging: hot fluid in → cold fluid out
  - ✓ Discharging: cold fluid in → hot fluid out
- Hot and cold fluid is separated by thermal stratification
  - ✓ Thermocline formation
- Packed bed thermal energy storage
  - ✓ Randomly packed solid filler in cylindrical tank
  - ✓ Heat storage through convective heat transfer
  - ✓ Cost effective



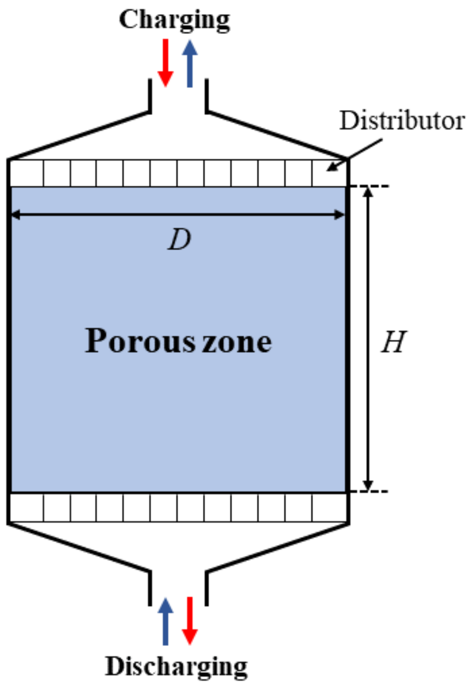
Principle scheme of packed bed TES
[Baeuerle, 2017]

Object of present study

- Parametric study of packed bed TES using numerical analysis
  - ✓ Numerical evaluation of thermal performance varying design parameter
    - I. Flow velocity (*u*)
    - II. Tank height (*H*)
    - III. Porosity (ε)
    - IV. Heat transfer fluid
- Provide basic data for packed bed TES system design

Model description

Parameters of packed bed TES



Packed bed TES

Design parameters

Parameters	Values
Hear transfer fluid	Molten salt
Solid filler	Quartzite rock
Tank height [m]	6
Tank diameter [m]	3
Filer diameter [m]	0.01905
Initial hot temperature [K]	663.15
Initial cold temperature [K]	563.15
Flow velocity [m/s]	0.001
Porosity	0.22

- In this work, the discharging process was simulated and analyzed
- Distributors are installed near the tank`s inlet and outlet to ensure uniform flow distribution

Parametric study

Test matrix of packed bed TES

Parameters	Values
Flow velocity [m/s]	5×10^{-4} –3×10^{-3}
Tank height [m]	2–8
Porosity	0.12–0.42
Heat transfer fluid	Molten salt Therminol-66 Liquid sodium

- Varied parameters

    I. Flow velocity (*u*)

    II. Tank height (*H*)

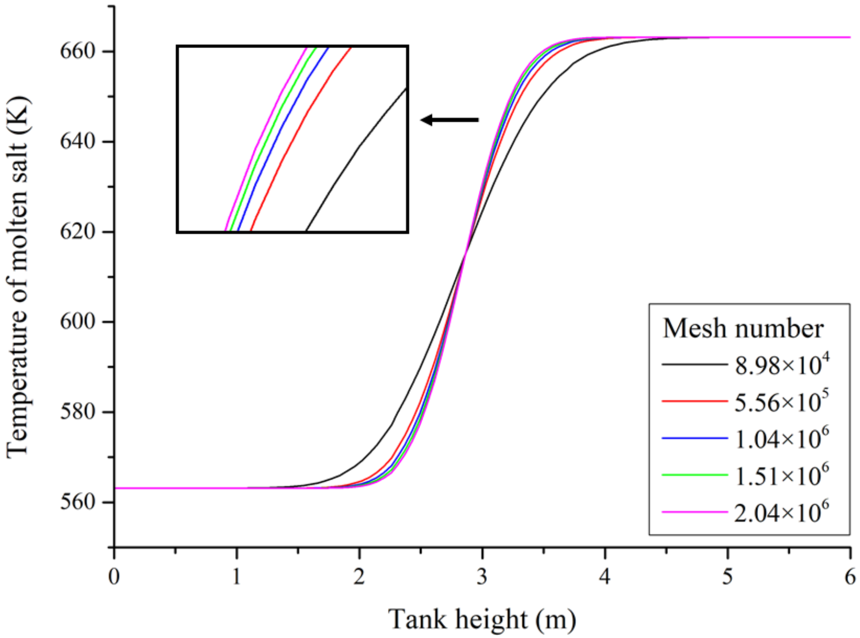
    III. Porosity (ε)

    IV. Heat transfer fluid

Numerical method

- Simulation was performed by adopting the CFD code based on **ANSYS Fluent**
- Three-dimensional flow was simulated in transient mode
- Assumptions
  - I. Uniform flow of constant velocity is injected into the tank
  - II. Flow motion is laminar
  - III. Packed bed region is insulated (adiabatic condition)
  - IV. The properties of working fluid and solid filler are independent of temperature
- PISO algorithm is used for the pressure-velocity coupling
- Time step size is 1 s and residual is 10^{-4}

Sensitivity analysis



Mesh sensitivity analysis

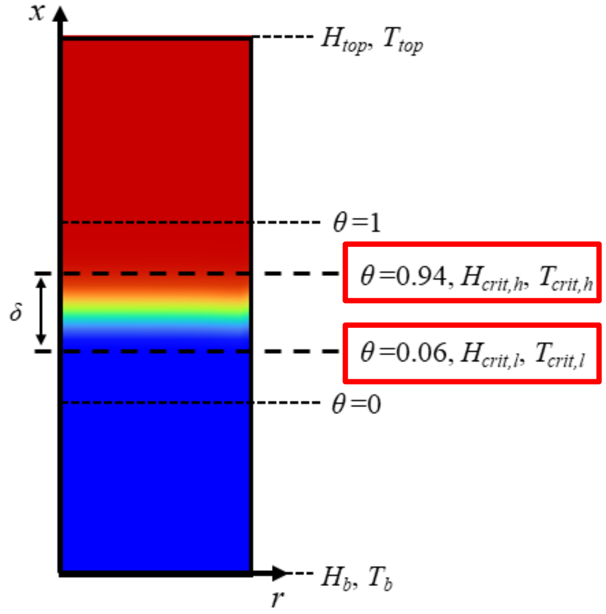
Table for mesh number

Mesh size [m]	**Mesh number**
0.1	89,877
0.05	556,157
0.04	1,042,880
0.035	1,507,843
0.032	2,043,586

- Since the case for 5.56×10^5, the maximum relative error has decreased by 0.8 %
- The case for 1.04×10^6, was adopted in consideration of the error rate and calculation time

Thermal performance indicator

- **Thermocline thickness**



$$\theta = \frac{T_l - T_c}{T_h - T_c} \qquad (1)$$

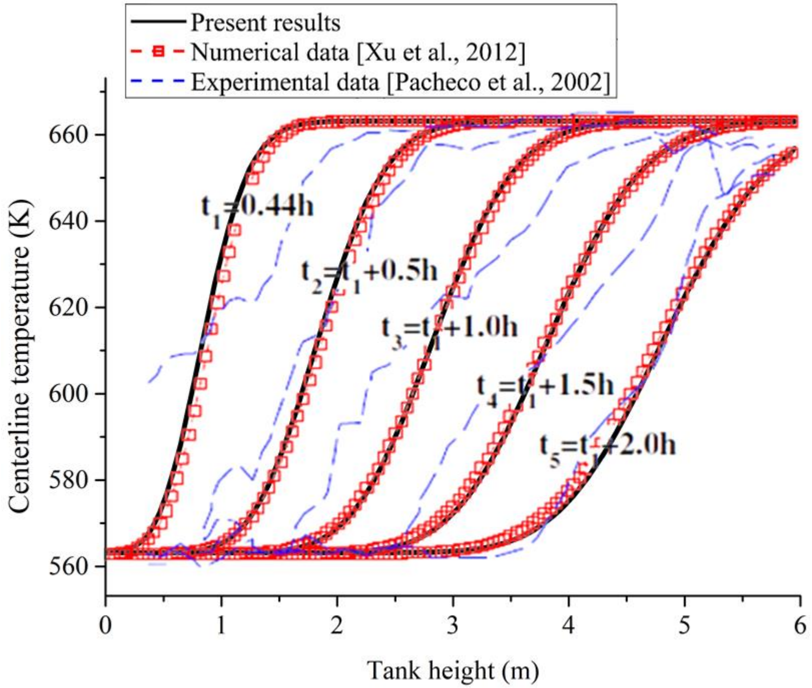
$$\delta = \begin{cases} H_{crit,h} - H_{crit,l} & (T_b \le T_{crit,l} \text{ and } T_{top} \le T_{crit,h}) \\ H_{crit,h} - H_b & (T_b > T_{crit,l}) \\ H_{top} - H_{crit,h} & (T_{top} > T_{crit,h}) \end{cases} \qquad (2)$$

- **Energy efficiency**

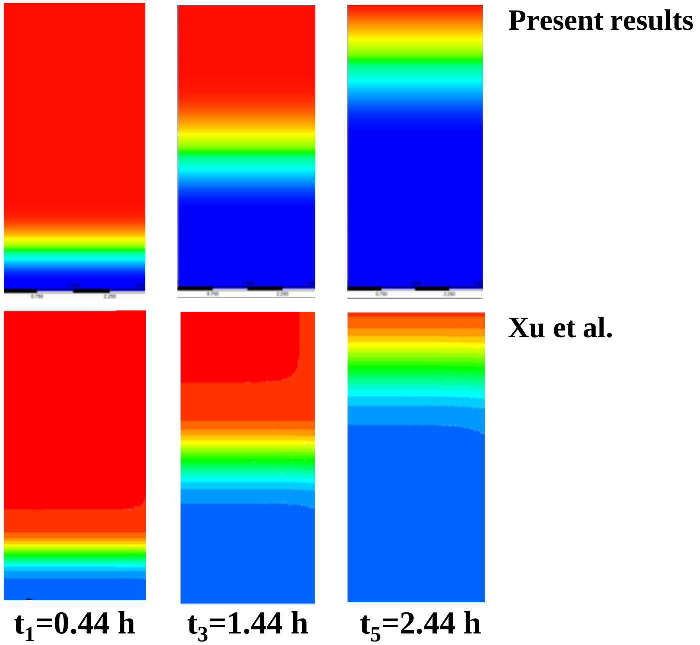
$$\eta = \frac{\int_0^{t_{dischar.}} \dot{m}\, C_{p,f}[T_{f,out}(t) - T_{cold}]dt}{\int_0^{t_{char.}} \dot{m}\, C_{p,f}[T_{hot} - T_{cold}]dt} \qquad (3)$$

Results and discussion

Validation

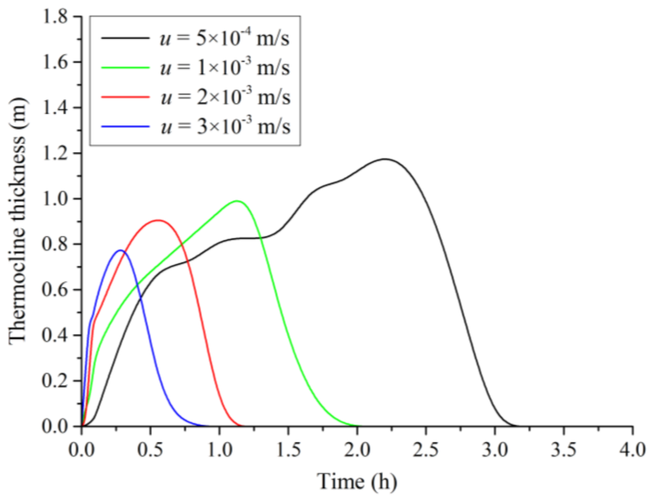


Model validation

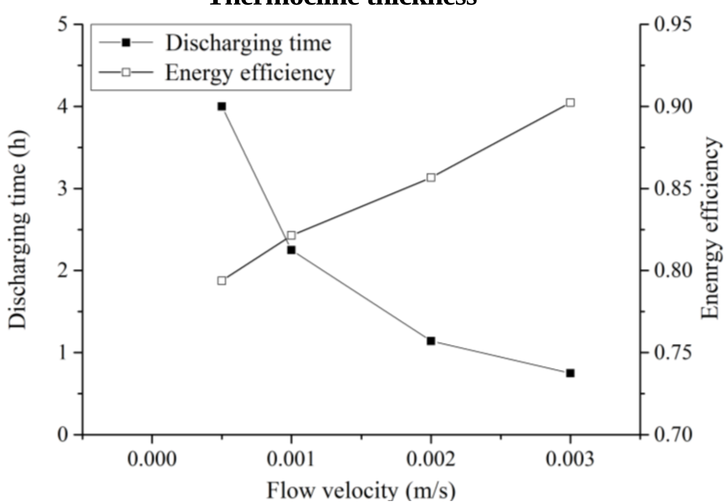


- The numerical results were compared with the results of existing study
  - ✓ Average relative error = 2.1 %

Influence of flow velocity



Thermocline thickness



Discharging time and energy efficiency

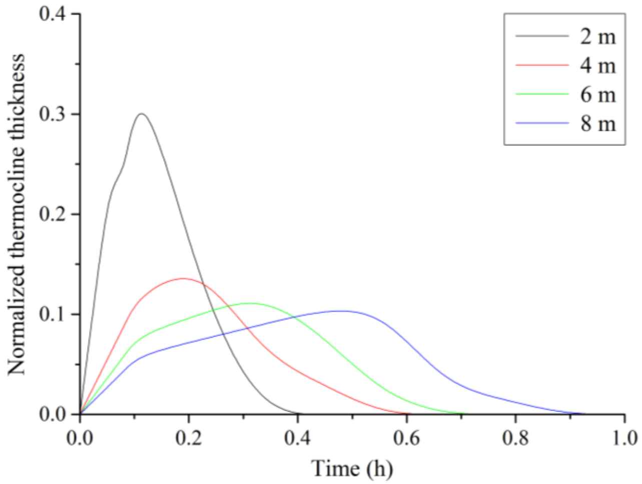
Results of study for flow velocity

Flow velocity [m/s]	Thermocline thickness [m]	Discharging time [h]	Energy efficiency
5×10^{-4}	0.354	0.28	0.748
1×10^{-3}	0.152	0.47	0.840
2×10^{-3}	0.120	0.64	0.869
3×10^{-3}	0.105	0.81	0.884

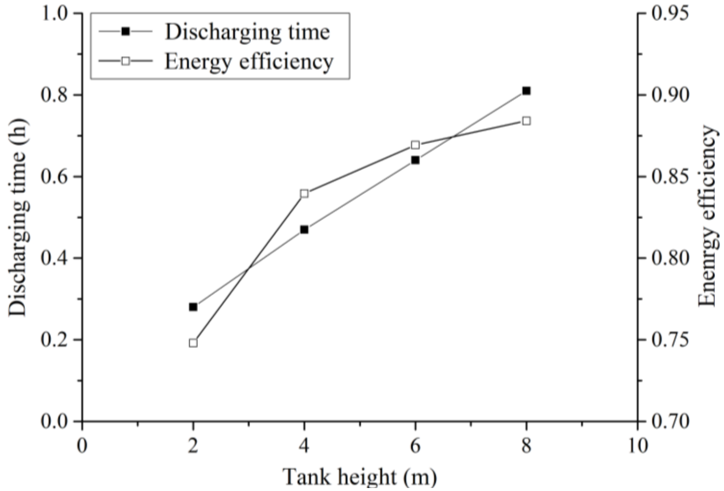
H = 6 m, ε = 0.22, molten salt, discharging mode

- u ↑, thermocline thickness ↓, Efficiency ↑
  - ✓ Heat transfer between the fluid and the solid filler was improved
  - ✓ Residence time of the thermocline within the tank was shortened

Influence of tank height



Thermocline thickness



Discharging time and energy efficiency

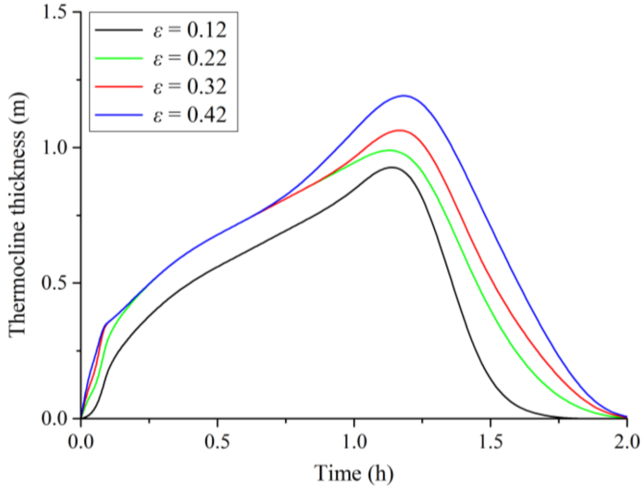
Results of study for tank height

Tank height [m]	Normalized thermocline thickness	Discharging time [h]	Energy efficiency
2	0.354	0.28	0.748
4	0.152	0.47	0.840
6	0.120	0.64	0.869
8	0.105	0.81	0.884

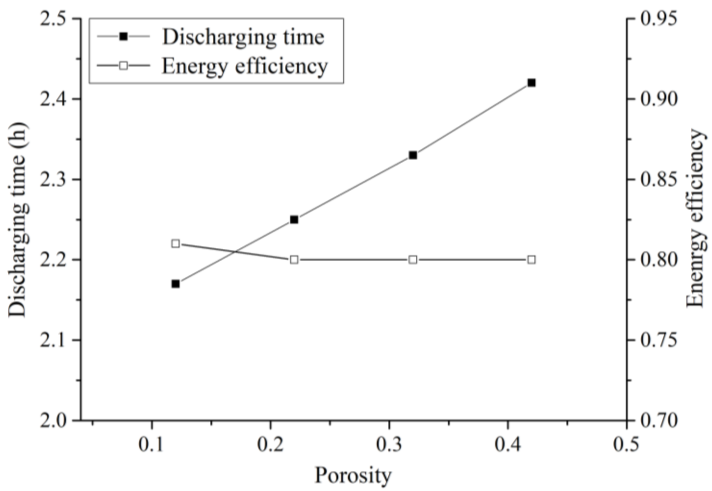
u = 3×10^{-3} m/s, ε = 0.22, molten salt, discharging mode

- Thermocline thickness normalized according to tank height
- *H* ↑, thermocline thickness ↑
  - ✓ Expansion time of thermocline has increased
- *H* ↑, normalized thermocline thickness ↓, Efficiency ↑
  - ✓ Increase in storage capacity had a greater impact on efficiency

Influence of porosity



Thermocline thickness



Discharging time and energy efficiency

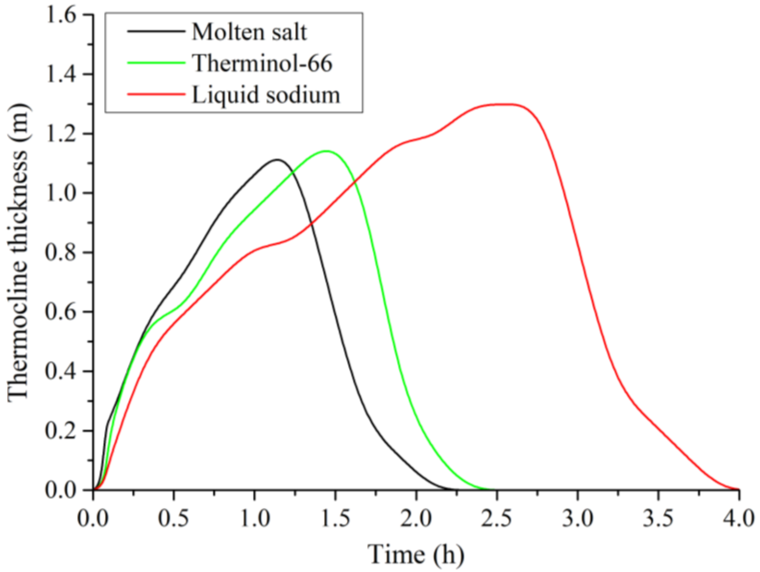
Results of study for porosity

Porosity	Thermocline thickness [m]	Discharging time [h]	Energy efficiency
0.12	0.826	2.17	0.807
0.22	1.062	2.25	0.804
0.32	1.181	2.33	0.801
0.42	1.298	2.42	0.798

u = 3×10^{-3} m/s, H = 6 m, molten salt, discharging mode

- ε ↑, thermocline thickness ↑
  - ✓ Reduced the heat transfer area of the solid filler and impaired the heat transfer between the fluid and solid filler
- Energy efficiency was similar in the all cases for porosity
  - ✓ Area of the fluid by the porosity compensated for this

Influence of heat transfer fluid



Results of study for HTF

Heat transfer fluid	Thermocline thickness [m]	Discharging time [h]	Energy efficiency
Molten salt	1.179	2.25	0.796
Therminol-66	1.184	2.86	0.840
Liquid sodium	1.298	3.97	0.775

u = 3×10^{-3} m/s, H = 6 m, ε = 0.22, discharging mode

- Molten salt showed the smallest thermocline thickness
- Therminol-66 showed the best energy efficiency
- Liquid sodium is bad for packed bed TES system
  - ✓ Low energy efficiency, long discharging time, high thermal conductivity

Conclusions and further studies

Conclusions

- Packed bed TES was simulated using numerical method and verified compared to results of existing study
- The influence of design parameters on packed bed TES was conducted
  - ✓ ***u*** ↑, thermocline thickness ↓, Efficiency ↑
  - ✓ ***H*** ↑, normalized thermocline thickness ↓, Efficiency ↑
  - ✓ ***ε*** ↑, thermocline thickness ↑

Further studies

- Parametric study for added the deign parameters
- Improved model for NPP system
- Effect of distributor on thermocline in TES

Thank you for attention.