Investigation of the performance of packed bed thermal energy storage system varying design parameters

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1. Introduction

As the renewable energy penetration increases in the electric grid systems, the energy intermittency issue arises due to its intrinsic limitation of the renewables [1, 2]. To sort out this issue, it is necessary to develop technologies for grid stability.

In most countries, Nuclear Power Plants (NPPs) are operated as the base load suppliers and the power control in response to the variations of the renewables is not easy even though some NPPs are equipped with load follow capabilities. The variations of the renewables are compensated either by a backup generator or an ESS (Energy Storage Systems). The former emits carbon-dioxide and the latter is too expensive. Hence, the thermal energy storage (TES) system is considered for flexible operation of NPPs [2].

The packed bed TES is one of the TES systems using packed bed in a tank. The charging and discharging of thermal energy are performed by heat transfer between heat transfer fluid and solid filler material [3].

With the packed bed TES system, the thermal stratification inside the tank can be formed and this phenomenon can separate hot and cold fluids in a single tank. This allows discharging of hot fluid even though the tank is not completely charged. The performance of packed bed TES depends on design parameters [4]. The present study investigated the performance of packed bed TES using a numerical model. As the performance criterion, storage efficiency was evaluated by varying solid filler diameter and storage height.

2. Present model description

2.1 One-dimensional two-phase (1D-2P) Model

Various numerical models were developed based on the Schumann's equation [5] to predict thermal behavior of packed bed TES. 1D means one-dimensional flow direction and 2P is different fluid and solid temperature. The 1D-2P model used in this study considered additional heat transfer phenomena from Schumann's equation such as heat conduction between heat transfer fluid (fluid) and heat conduction between solid filler material (solid) The assumptions for this model are as below:

I. A uniform and constant velocity of the flow is imposed at the tank inlet and outlet (Laminar flow regime).
II. Heat transfer between fluid and solid occurs only in the axial direction.
III. Solid filler is considered a continuous porous medium.
IV. The properties of solid filler are independent of the temperature.
V. Storage tank is well insulated (adiabatic boundary condition).

This numerical model is governed by the following energy balance Eqs. (2.1), (2.2):

Energy balance for fluid, *f*:

$$\varepsilon\rho_f C_{p,f}\frac{\partial T_f}{\partial t}+u_{sup}\rho_f C_{p,f}\frac{\partial T_f}{\partial x} = k_f\frac{\partial^2 T_f}{\partial x^2}+h\cdot a_s(T_s-T_f), \quad (2.1)$$

Energy balance for solid, *s*:

$$(1-\varepsilon)\rho_s C_{p,s}\frac{\partial T_s}{\partial t}=k_s\frac{\partial^2 T_s}{\partial x^2}+h\cdot a_s(T_f-T_s). \quad (2.2)$$

In these equations, ε is the porosity of the storage tank, k is effective thermal conductivity calculated by Xu et al. [4], superficial velocity, u_{sup}, is calculated as given in Eq. (2.3):

$$u_{sup}=\frac{\dot{m}}{\rho_f\pi\left(\frac{D^2}{4}\right)}. \quad (2.3)$$

Heat transfer coefficient, h, is calculated by the Nusselt number correlation of Wakao et al. [6] and a_s is the surface area of solid per unit volume as given in Eqs. (2.4) and (2.5) respectively:

$$Nu=2+1.1\cdot Re_d^{0.6}Pr^{1/3}, \quad (2.4)$$

$$a_s=\frac{6(1-\varepsilon)}{d_p}. \quad (2.5)$$

2.2 Numerical method

In order to predict thermal behavior of packed bed TES system, Eqs. (1) and (2) were numerically solved using an in-house code. The finite difference method was adopted and an implicit scheme was used for time discretization. At each time step, the temperature of the fluid and solid were calculated at the same time with a 10^{-6} convergence criterion. The in-house code was written in MATLAB software.

2.3 Initial and boundary conditions

Table I shows the initial and boundary conditions for numerical analysis. At initial condition, temperature of fluid and solid is constant. During charging and discharging, the inlet temperature is constant, and the outlet temperature is in adiabatic condition.

Table I: Initial and boundary conditions

	Fluid	**Solid**
Initial condition	T_f at t:0 = $T_{initial}$	T_s at t:0 = $T_{initial}$
Boundary condition (Inlet)	$T_f = T_{inlet}$	$T_s = T_{inlet}$
Boundary condition (Outlet)	$\frac{\partial T_f}{\partial x} = 0$	$\frac{\partial T_s}{\partial x} = 0$

2.4 Thermal performance evaluation

In order to evaluate storage performance, storage efficiency is introduced. Storage efficiency, η, is the most common way of estimating thermal storage performance, and can be expressed following Eq. (2.6) [7]:

$$\eta = \frac{\int_0^{t_{dischrage}} \dot{m} C_f \left[T_{f,\text{out}}(t) - T_{low} \right] dt}{\int_0^{t_{chrage}} \dot{m} C_f \left[T_{high} - T_{low} \right] dt}. \tag{2.6}$$

3. Results and discussion

3.1 Model validation

Our numerical model was validated by using Hoffmann et al.'s laboratory scale packed bed TES test results [8]. Fig. 1 compares the numerical results and the experimental results of Hoffmann et al. The temperature profiles according to storage tank height and time are plotted. Both results seem to be in good agreement.

3.2 Parametric study

To evaluate the performance of packed bed TES, the influences of some design parameters were explored. The design parameters for the present study are summarized in Table II. The types of heat transfer fluid and solid filler were selected by referring to Idaho National Laboratory's thermal energy distribution system [9]. In the present study, the performance evaluation of packed bed TES was conducted by varying solid filler diameter and storage tank height.

Table II: Design parameters for the present study

Parameters	
Tank height (m)	1–3
Tank diameter (m)	1
Solid diameter (mm)	3–15
Solid material	Alumina [9]
Heat transfer fluid	Therminol-66 [9]
Hot fluid temperature (K)	598
Cold fluid temperature (K)	498
Porosity	0.41

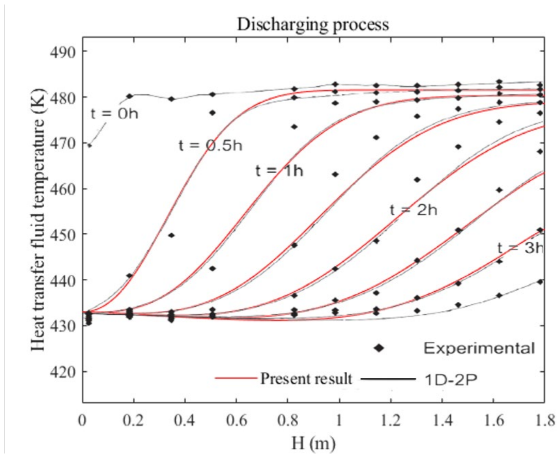

Fig. 1. Comparison of temperature profile between present study and existing study, modified from [8].

The influence of solid diameter was examined by varying the solid diameter by 3 mm to 15 mm. Fig. 2 shows the computed efficiency according to the solid diameter. The efficiency decreased with increasing solid diameter. As the solid diameter increases, the total heat transfer area decreases. Hence, the heat transfer region increases along the axial direction. Since this has a negative effect on thermal stratification, efficiency decreases.

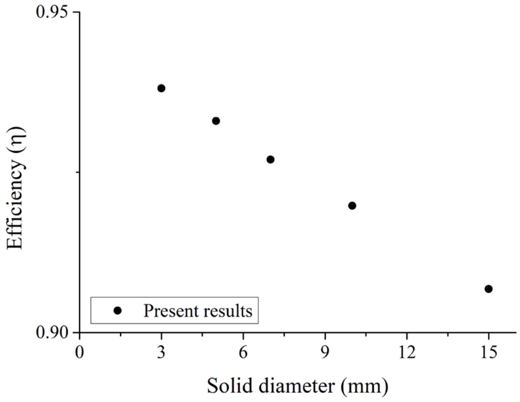

Fig. 2. Efficiency variations according to solid diameter.

Figure 3 shows the influence of storage tank height on thermal efficiency. The Height increased from 1 to 3 times compared to the tank diameter. The efficiency increased with increasing tank height. Storage tank height affects storage capacity. As the height increases, total storage capacity increases. But, the area where hot and cold fluid meet is the same, the efficiency increases as tank height increases. Also, the time for charging and discharging increases with the increasing tank height. Then thermal stratification is negatively affected by heat conduction of fluid. However, in this research, the increase in efficiency by the storage capacity was more dominant.

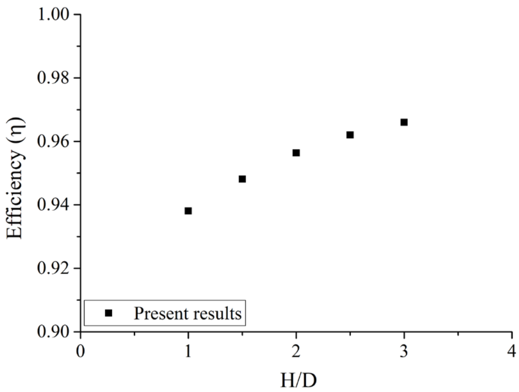

Fig. 3. Efficiency variations according to tank height.

4. Conclusions

Thermal performance of packed bed TES was evaluated using an in-house code developed to calculate the fluid and solid temperatures when charging and discharging. The storage efficiency was chosen as the thermal performance criterion and numerical calculation were performed varying solid diameter and tank height. The storage efficiency decreased with increasing solid diameter and increased with increasing tank height. Through a parametric study of packed bed TES, the authors expect that present study will be utilized as basic data for packed bed TES design.

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REFERENCES

[1] A. Bruch, S. Molina, T. Esence, J. F. Fourmigue, R. Couturier, Experimental investigation of cycling behaviour of pilot-scale thermal oil packed-bed thermal storage system, Renewable Energy, Vol. 103, pp. 277–285, 2017.
[2] J. Y. Heo, J. H. Park, Y. J. Chae, S. H. Oh, S. Y. Lee, J. Y. Lee, N. Gnanapragasam, J. I. Lee, Evaluation of various large-scale energy storage technologies for flexible operation of existing pressurized water reactors, Nuclear Engineering and Technology, Vol. 53, pp. 2427–2444, 2021.
[3] G. Li, Sensible heat thermal storage energy and exergy performance evaluations, Renewable and Sustainable Energy Review, Vol. 53, pp. 897–923, 2016.
[4] C. Xu, Z. Wang, Y. He, X. Li, F. Bai, Sensitivity analysis of the numerical study on the thermal performance of a packed-bed molten salt thermocline thermal storage system, Applied Energy, Vol. 92, pp. 65–75, 2012.
[5] T. E. W. Schumann, HEAT TRANSFER: A LIQUID FLOWING THROUGH A POROUS PRISM, Journal of the Franklin Institute, Vol. 208, pp. 405–416, 1929.
[6] N. Wakao, S. Kaguei, T. Funazkri, Effect of fluid dispersion coefficients on particle-to-fluid heat transfer coefficients in packed beds, Chemical Engineering Science, Vol. 34, pp. 325–336, 1979.
[7] J. T. Van Lew, P. Li, C. L. Chan, W. Karaki, J. Stephens, Analysis of heat storage and delivery of a thermocline tank having solid filler material, Journal of Solar Energy Engineering, Vol. 133, 2011.
[8] J. F. Hoffmann, T. Fasquelle, V. Goetz, X. Py, A thermocline thermal energy storage system with filler materials for concentrated solar power plants: Experimental data and numerical model sensitivity to different experimental tank scales, Applied Thermal Engineering, Vol. 100, pp. 753–761, 2016.
[9] K. Frick, S. B. Sitton, C. Rabiti, Modeling the Idaho National Laboratory Thermal-Energy Distribution System (TEDS) in the Modelica Ecosystem, Energies, Vol. 13, pp. 1–25, 2020.