Effect of Aspect ratio on Performance of Packed Bed for Thermal Energy Storage

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1. Introduction

To address global challenges related to climate change and energy sustainability, efficient utilization of renewable energy sources such as solar, wind, and hydropower is essential. However, the intermittency of these sources poses challenges for maintaining a stable electricity supply. To mitigate this, energy storage systems (ESS), particularly Thermal Energy Storage (TES), play a crucial role in stabilizing power generation [1]. TES is favored due to fewer location and duration constraints, allowing integration with renewable energy and nuclear power sources to mitigate grid variability caused by renewable intermittency and load demand fluctuations [2,3].

Using TES, which can be mechanically integrated at the low-pressure turbine inlet of a Nuclear Power Plant (NPP), helps address load-following issues. By storing excess heat from the reactor, the TES system enhances the reactor's output stability and enables smoother operations. Molten salts are effective sensible heat media due to their high specific heat, wide temperature range (220–600°C), and low corrosivity [4], which makes them a prominent candidate for effective heat transfer media in TES systems.

TES systems are categorized by architecture, such as two-tank, thermocline, and packed bed systems, and by storage mechanism: sensible and latent heat. Sensible heat storage raises the temperature of a material, while latent heat storage uses phase change materials (PCMs) for energy absorption and release, as shown Fig.1. TES systems can also be classified as direct or indirect, depending on whether the same fluid is used for heat transfer and storage. Indirect systems, though more complex, allow for independent optimization of heat transfer fluid (HTF) and storage media, potentially improving energy density. One of the examples of an indirect TES system is a packed bed system.

A challenge for packed bed TES systems is maintaining stable discharge temperatures due to temperature stratification and internal thermal imbalances. This study employs GAMMA+, a multidimensional heat transfer simulation tool, to investigate the impact of aspect ratio and particle size on temperature distribution and performance [5]. It is expected that optimizing the aspect ratio will reduce stratification and improve thermal uniformity, while selecting the optimal particle size will enhance heat transfer efficiency. This study provides important data for optimizing packed bed TES systems for SMRs and nuclear-integrated configurations, contributing to improved thermal efficiency and supporting the integration of renewable energy with nuclear power.

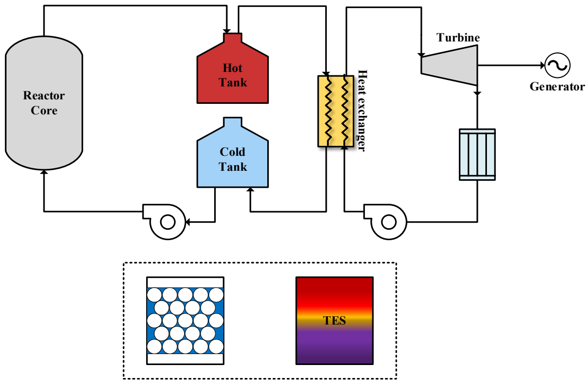

Fig 1. Overall schematic layout of TES operating diagram, two-tank (top), packed bed (left), and thermocline (right)

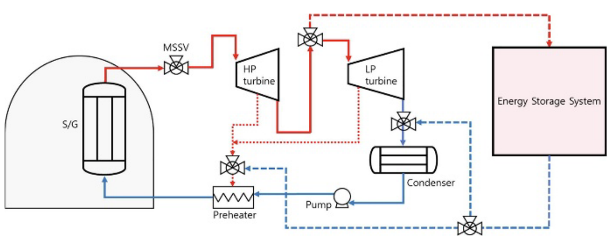

Fig 2. Conceptual diagram of integrated steam cycle of PWR power plants with energy storage system [6]

2. Methods and Results

2.1 Heat transfer Theory in GAMMA+

The GAMMA+ multi-dimensional heat conduction model incorporates a structured mesh in rectangular, cylindrical, and spherical coordinates. In the 2D model, calculations are carried out using axial and radial nodes, with the resolution adjustable based on the computational requirements; however, excessively refining the nodes may lead to a substantial increase in simulation time. As a result, this study divides the packed bed into a 10 axial × 5 radial node configurations to analyze the thermal phenomena dominated by effective heat conduction.

$$\varphi_s(\rho c_p)\frac{\partial}{\partial} = \frac{\partial}{\partial x_i}\left(\lambda_{eff,i}\frac{\partial T}{\partial x_i}\right) + q''' + q'''_{wall-to-fluid} \quad (1)$$

$$\varphi_s = 1 - \varphi \tag{2}$$

φ_s is the solid volume fraction in the porous medium. The q''' is the volumetric heat source, and $q'''_{wall-to-fluid}$ is the volumetric heat transfer rate between the wall and fluid. However, there is no volumetric heat source in this study.

For convection in a porous medium, the solid-to-fluid heat transfer coefficient and the specific interfacial area relation are given in equation (3), while the solid-to-solid thermal conductivity is calculated using equation (6), both based on the Zehner and Schlünder correlation for heat transfer through a unit cell. The heat transfer paths across a cell and built into GAMMA+ code, are as follows:

1) Conduction - radiation - conduction
2) Direct radiation across the entire cell

Each cell's temperature is computed by pairing corresponding nodes in a unit cell and applying heat transfer correlations, such as effective conductivity between solid spheres and heat transfer fluid (HTF).

$$q''' = h_{sf} a_{sf} (T_s - T_f) \tag{3}$$

$$h_{sf} = \frac{\lambda_f}{d_p}\left(1.27 \frac{Pr^{\frac{1}{3}}}{\varphi^{1.18}} Re_p{}^{0.36} + 0.033 \frac{Pr^{\frac{1}{2}}}{\varphi^{1.07}} Re_p{}^{0.86}\right) \tag{4}$$

$$a_{sf} = \frac{6(1-\varphi)}{d_p}, \quad Re_p = \frac{\rho U d_p}{\mu} \tag{5}$$

$$\lambda_{eff} = \lambda_{eff}{}^{void-radiation} + \lambda_{eff}{}^{gas-conduction} + \lambda_{eff}{}^{contact-conduction} \tag{6}$$

where h_{sf} is the solid-to-fluid heat transfer coefficient, a_{sf} is the specific interfacial area, d_p is the diameter of particle(solid) and the subscript *sf,* and *f* indicate solid-to-fluid, and fluid, respectively. λ_f is fluid thermal conductivity, λ_{eff} is fluid effective thermal conductivity, *Pr* is the Prandtl number, and Re_p is the Reynold number of porous fluid.

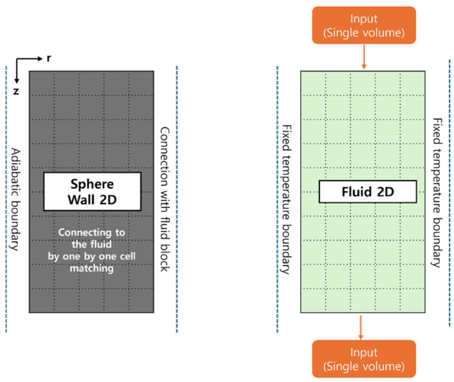

Fig 3. Nodalization of heat structure and fluid for packed bed modeling in GAMMA+

2.2 Validation with the Experiment

To validate the packed bed model for sensible heat storage using GAMMA+, the simulation results were compared with experimental data from the Sandia Lab prototype, as reported by Pacheco [7]. The experiment involved a pilot-scale packed bed thermal energy storage system, where temperatures were recorded during discharging with molten salts, quartzite rock, and silica filter sand as filler materials. The setup included a cylindrical steel vessel filled with the packed bed, with thermocouples placed vertically at 15 cm intervals. During the test, 289°C solar salt was injected from the top to cool the packed bed, which was assumed to be fully charged. The experimental configuration parameters are summarized in Table 1 [7]. Figure 4 compares the temperature profiles predicted by the model and the experimental data. The experimental results (dots) and GAMMA+ simulation results (line) show minor deviations, suggesting that the model accurately captures the transient temperature distribution. The average MAPE (Mean Absolute Percentage Error) over the 2-hour simulation, recorded at 30-minute intervals, was 3.80%. And the MAPE is mathematically defined as the deviation for each point n at time t between the measured value of the variable $\tilde{x}_t$ and the value of the variable obtained from the simulation x_t. Based on these results, it can be concluded that the GAMMA+ model reliably predicts the heat transfer behavior in real sensible heat storage packed bed systems.

$$MAPE\ (\%) = \frac{100}{n} \sum_{t=1}^{n} \left| \frac{\tilde{x}_t - x_t}{\tilde{x}_t} \right| \tag{7}$$

Table. 1 Sandia Lab's Experimental set-up parameters

Parameters	**Value**	**Unit**
Height	6	m
Internal Diameter	3	m
Porosity	0.22	
Heat transfer fluid (HTF)	Solar Salt	
HTF mass flow	3.7	kg/s
Charge HTF temperature	395.9	C
Discharge HTF temperature	289	C
Packing material	Rock and Sand	
Particles diameter	0.19	cm
Solid specific heat capacity	0.84	kJ/kgK
Solid density	2690	kg/m^3
Solid conductivity	2.4	W/mK

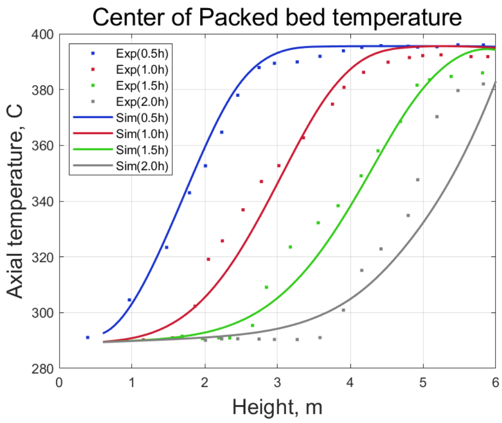

Fig 4. Validation result of Sensible heat stored in molten salt packed bed

2.3 Packed bed model

The design parameters of the GAMMA+ packed bed model, which includes the geometric parameters, are summarized in Table 2.

For sizing the Packed bed, the following assumptions are made:

1) The designed packed bed system is cylindrical type.
2) Concrete particles are in packed bed mono-sized spheres which are packed randomly, resulting in a system porosity of 0.36 regardless of particle size [9].
3) The packed bed system can be designed to align with 240MWh.
4) The thermal efficiency of SMR is assumed to be 0.45.

For calculations, the thermal property variations of concrete are considered, as the charging and discharging of heat using high-temperature molten salt significantly influences its thermal properties [10].

Table. 2 Design parameters of Packed bed

Parameters	**Value**	**Unit**
Height	37.71	m
Internal Diameter	9.0	m
Porosity	0.36	-
Heat Transfer Fluid (HTF)	Solar salt	
Charging HTF mass flow	1169.3	kg/s
Charging HTF Inlet temperature	550	°C
Charging HTF time	1.5	hour
Ambient temperature	20	°C
Packing material	Concrete	
Particles diameter	0.03	m
Particles density	2067	kg/m^3
Particles thermal conductivity	2.20	W/mK
Particles specific heat	1.160	kJ/kgK

2.4 Effect of Aspect ratio on temperature

The aspect ratio (H/D) of a packed bed plays a crucial role in its thermal performance. By adjusting the height and diameter, the aspect ratio can be altered while maintaining constant volume, ensuring that the energy storage capacity remains largely unchanged. This study explores the packed bed system by varying its height and diameter, with other parameters consistent with the base case outlined in Table 2.

Simulations were conducted with diameters (D = 8, 7, 6, 5, 4.5, and 4.25 m), resulting in aspect ratios (AR) of 0.74, 1.06, 1.77, 3.06, 4.19, and 4.97. Figure 6 shows the outlet solar salt temperature distribution at 1.5 hours of charging for different aspect ratios. The results reveal that lower aspect ratios cause greater temperature non-uniformity and increased radial thermal gradients, as reflected by the RMSE values ranging from 33.25 to 0.22.

Higher aspect ratios, on the other hand, improve thermal mixing and yield a more uniform temperature distribution. For aspect ratios below 1.7, significant temperature variations across the radial nodes are observed, which prolongs charging times. However, when the aspect ratio exceeds 3, the temperature distribution becomes more uniform, enhancing thermal mixing and reducing thermal gradients. Figure 5 illustrates this effect, where lower aspect ratios show limited heat exchange near the tank sides, slowing the temperature increase. In summary, the aspect ratio influences heat transfer by altering the flow path and mixing within the packed bed. With a low aspect ratio, heat exchange at the tank walls becomes more pronounced, leading to greater radial temperature non-uniformity. In contrast, a high aspect ratio promotes more effective axial heat transfer, resulting in a more uniform temperature distribution and improved energy storage efficiency.

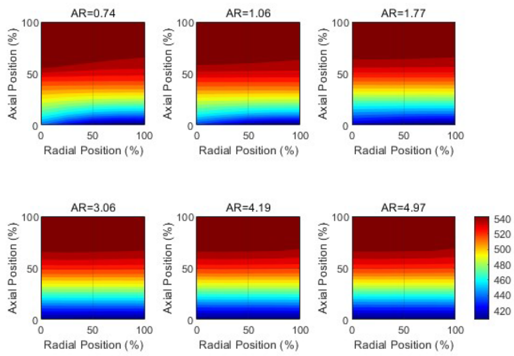

Fig 5. Temperature distribution in Packed bed for different aspect ratio at 1.5 hours charging

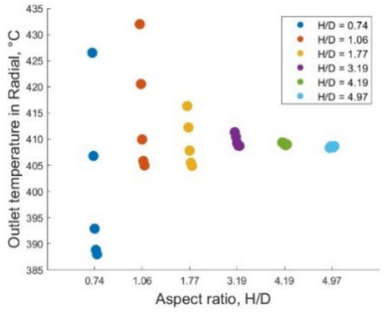

Fig 6. Temperature difference in radial direction of Packed bed for different aspect ratio

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y}_i - y_i)^2}{n}} \qquad (7)$$

where $\hat{y}_i$ is the reference outlet temperature, which in this paper is the temperature at the center, and y_i represents the outlet temperatures at other radial positions. Therefore, the RMSE quantifies the radial temperature inhomogeneity corresponding to each aspect ratio.

2.4.1 Effect of Aspect ratio on Charging

In the numerical modeling for calculation, a structured nodal approach is employed to accurately estimate spatial temperature variations by assigning nodes in both radial and axial directions, ($N_r \times N_z = 5 \times 10$) as shown in Table 3.

Table. 3 Position corresponding to the Node for calling

Number	Location in PB	Coordinate
$N_r = 1$	Center	r = 0
$N_r = 5$	Outermost	r = R
$N_z = 1$	HTF inlet	z = 0
$N_z = 10$	HTF outlet	z = H

$$Q_{charge} = \int_0^t \dot{m}_{salt}\left(T_{t+1}c_{p,t+1} - T_t c_{p,t}\right)dt \qquad (8)$$

where $\dot{m}_{salt}$ is the solar salt mass flow rate, $c_{p,t}$ denotes the specific heat of the salt. Q_{charge} is calculated as the heat transferred from salt to the packed bed system during the charging process. Using the transferred heat of the salt and the charging period, the average charging rate can be determined by dividing the total transferred heat by the total charging duration.

The charging rate of the packed bed is an indicator that reflects the impact of thermal dispersion within the packed bed. The charging rate is calculated using the conservation of energy methodology, once the thermal behavior has been determined by GAMMA+, as given in equation (8).

To fully understand and quantify the charging process based on aspect ratio, the instantaneous charging rates and accumulated charging capacities were calculated and presented in Figures 7 and 8. In the case of a high aspect ratio, the peak value is higher due to the efficient heat transfer between the HTF and the storage media.

As a result, this case requires less energy input compared to the other two cases to fully charge the bed, leading to faster charging times. The larger temperature difference between the inlet and outlet causes higher instantaneous charging capacity, which results in a higher total charging capacity at the end of the process. Therefore, in the case of a higher aspect ratio, thermal dispersion is more effective, and there is a clear advantage in terms of charging time.

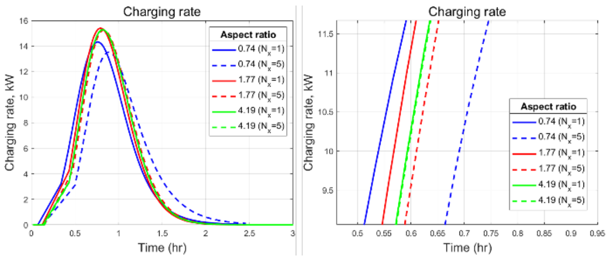

Fig 7. Charging rate in radial direction of Packed bed at aspect ratio (left) and detail (right)

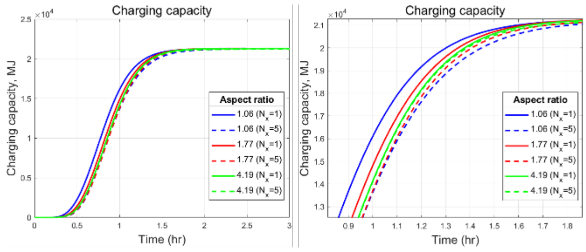

Fig 8. Charging capacity in radial direction of Packed bed at aspect ratio (left) and detail (right)

3. Conclusions and future study

In this study, the performance of the packed bed system as a thermal energy storage (TES) system was analyzed, with a particular focus on the impact of the aspect ratio (H/D) on thermal efficiency, charging rate, and charging time. The results demonstrate that the aspect ratio plays a crucial role in the thermal performance of the packed bed. By adjusting the height and diameter, the aspect ratio can be modified while maintaining the overall volume, thereby preserving the energy storage capacity.

Simulation results confirm that a higher aspect ratio leads to more effective thermal mixing, reducing radial temperature gradients and consequently shortening the charging time. In contrast, a lower aspect ratio induces greater temperature non-uniformity, leading to increased charging time. This study highlights the significant role of aspect ratio selection in enhancing heat transfer efficiency and thermal uniformity, emphasizing the need for geometric parameter optimization for efficient energy supply in integrated nuclear power systems.

Future research should quantitatively investigate the impact of geometric parameters on TES performance in nuclear power-integrated systems. This will contribute to the design and optimization of packed bed TES systems, improving overall performance.

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