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Preliminary validation of GAMMA+ code for Packed bed thermal storage system

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1. Introduction

In addressing the need for solutions to climate change and promoting global sustainability in energy consumption, renewable energy sources such as solar, wind, and hydropower have emerged as critical components. Despite their potential to reduce CO_2 emissions in many countries, these sources face challenges due to their intermittency. Energy Storage Systems (ESS) offer a sustainable solution for stabilizing the electricity supply from individual plants to entire countries. ESS can shift demand peak by storing excess heat or electricity during periods of low demand and releasing it when power is scarce, complementing various forms of power generation, including nuclear.

Among many options for large-scale energy storage systems (ESS), liquefied air energy storage (LAES) is emerging as a solution. LAES works by liquefying air during off-peak hours and then evaporating it during peak demand hours to generate electricity with an air turbine while storing the heat generated in a thermal storage system as shown in Figure 1. Compared to other large-scale energy storage systems, LAES has many advantages, including high energy density, low geographical constraints, use of eco-friendly operating fluids, and extended service lifetime. These characteristics allow LAES installations to be strategically located close to regions with high electricity demand [1]. As a result, LAES is proving effective in addressing various challenges, including load leveling, peak shaving, frequency control, energy oscillation damping, and improving power quality and reliability.

The Korean Agency for Infrastructure Technology Advancement (KAIA) has initiated the Korean LAES demonstration project, with plans to establish a 2MW/6MWh LAES pilot plant [2]. However, a demonstrated LAES pilot plant has been reported to have a round-trip efficiency of 25% [Highview power, 3,4], and numerous studies are currently underway to overcome the low round-trip efficiency of LAES.

Packed bed thermal storage offers promising characteristics for liquid air energy storage (LAES) applications, including high thermal efficiencies (often over 85%), cost-effectiveness, and stringent safety standards. These characteristics make it an ideal choice for LAES systems. The cylindrical vessel filled with solid particles in packed beds enhances mass transfer through increased surface area interaction between particles and fluid. This configuration ensures efficient energy storage and retrieval, perfectly aligned with the requirements of LAES operation. Accordingly, the impact of thermal storage on the operation and performance of other components of an LAES plant presents challenges.

Therefore, this paper focuses on the validation of a packed bed to evaluate how well the performance matches to take advantage of its transient characteristics. The validation study was performed using GAMMA+ (General Analyzer for Multi-component and Multi-dimensional Transient Applications) transient code developed by KAERI (Korea Atomic Energy Research Institute). GAMMA+ serves as a system best-estimate analysis tool that calculates the thermal and fluid flow behavior during expected and postulated transients for high-temperature gas-cooled reactors (HTGRs). GAMMA+ includes several features, including a non-equilibrium porous media model for pebble bed and prismatic reactor cores, multi-dimensional fluid flow and heat conduction in rectangular and cylindrical coordinates, a thermal radiation model, point reactor kinetics, and special component models such as pumps, coolers, turbine compressors, valves, and control models. Specifically, in this study, the validation of uniform rock sphere-packed bed heat transfer was performed with GAMMA+ and compared with experimental results [5].

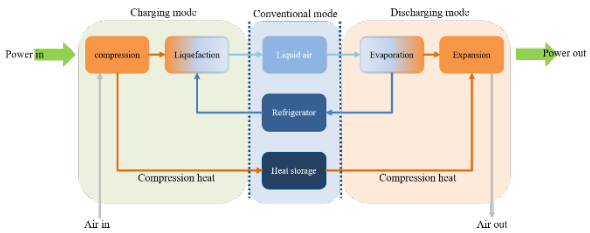

Figure 1. Diagram of LAES process

2. Methods and Results

2.1 Heat Transfer Theory in Gamma

GAMMA+ code is divided into Fluid and Wall cards for 1/2/3 Dimension and can perform the complicated thermodynamic calculation in a unit cell. In this study, the wall and fluid were modeled in 2-dimensional cylindrical coordinates as shown in Figure 2, due to the shape of the packed bed. The temperature and pressure of each cell of fluid and wall were calculated by connecting and matching one by one cell of the entire nodes in a unit cell. Therefore, a correlation for each unit cell is used to calculate the heat transfer such as an effective conductivity between the solid spheres and the air in a packed bed as shown in Figure 3.

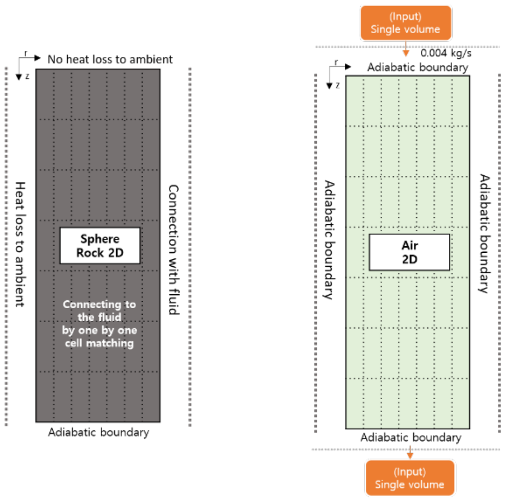

Figure 2. Nodalization of heat structure and fluid for packed bed modeling in GAMMA

The packed bed wall and fluid modeled in two dimensions and the fluid card in GAMMA can be set as boundary conditions on the top, bottom, left, and right, respectively, as shown in Table 1.

Table 1. GAMMA wall and fluid boundary conditions

position	Fluid	Wall
Top	Adiabatic	Adiabatic
Bottom	Adiabatic	No heat loss to ambient
West	Adiabatic	Connection with fluid
East	Adiabatic	Heat loss to ambient

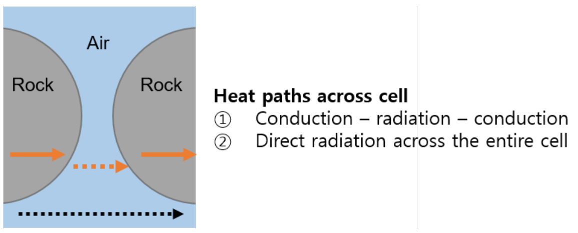

Figure 3. Effective conductivity considered in a packed bed in a unit cell

2.1.1 Multi-Dimensional Heat Conduction

In this study, the GAMMA+ multi-dimensional heat conduction model for packed bed is based on the structured mesh in cylindrical coordinates. The multi-dimensional heat conduction with a heat source is calculated by Equation (1).

$$\varphi_s(\rho c_p)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x_i}\left(\lambda_{eff,i}\frac{\partial T}{\partial x_i}\right)+q'''+q'''_{wf} \qquad (1)$$

$$\varphi_s = 1-\varphi \qquad (2)$$

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

2.1.2 Wall-to-Fluid Heat Transfer

For the convection of gas in a porous medium, the solid-to-fluid heat transfer coefficient, and the specific interfacial area relation are given in equation (3).

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

$$a_{sf}=\frac{6(1-\varphi)}{d_p} \qquad (4)$$

2.1.3 Effective Conductivity

The effective thermal conductivity of the packed bed includes the contributions of the thermal radiation in the void region, the conduction of gas, and the contact conduction of spherical pebbles as shown in the right of Figure 3.

The contact area between the pebbles depends on the material properties and the magnitude of the inter-pebble forces. Heat may pass between adjacent pebbles by conduction across these contact areas. The effective conductivity of the pebble bed is dependent on both the size of the contact area and the number of contact points between pebbles. The effective conductivity resulting from pebble-to-pebble conduction is calculated as the sum of the following equation (5)-(9) in GAMMA+.

$$\lambda_{eff}{}^{gas-conduction}=\lambda_f\left\{\begin{matrix}1-\sqrt{1-\varphi}\,\frac{\sqrt{1-\varphi}}{1-\lambda_r B}\\ \left[\frac{(1-\lambda_r)B}{(1-\lambda_r B)^2}\ln\left(\frac{1}{\lambda_r B}\right)-\frac{B+1}{2}-\frac{B-1}{\lambda_r B}\right]\end{matrix}\right\} \qquad (5)$$

$$\lambda_{eff}{}^{contact-conduction}==\lambda_s\left[\frac{3(1-\mu_p{}^2)}{4E_s}\frac{P_e S_F}{N_A}\frac{d_p}{2}\right]^{\frac{1}{3}}\frac{1}{0.531S}\left(\frac{N_A}{N_L}\right) \qquad (6)$$

$$\lambda_{eff}{}^{void-radiation}=\left\{\begin{matrix}[1-\sqrt{1-\varphi}]\varphi\,\frac{\sqrt{1-\varphi}}{2/\varepsilon_r}\,\frac{B+1}{B}\\ \left[1+\frac{1}{(2/\varepsilon_r-1)\Lambda}\right]^{-1}\end{matrix}\right\}4\sigma T^3 d_p \qquad (7)$$

$$B=1.25\left(\frac{1-\varphi}{\varphi}\right)^{\frac{10}{9}} \qquad (8)$$

$$\Lambda=\frac{\lambda_s}{4\sigma T^3 d_p} \qquad (9)$$

2.2 Modeling for Validation with the Experiment

It is important to ensure that the GAMMA+ code is suitable for simulating thermal energy storage packed beds, as it was originally developed for HTGR transient behavior. Therefore, the authors wanted to validate the system code results with experiments. The experiment was conducted with a constant flow rate of hot air flowing through a packed bed consisted of spherical stones [5]. The schematic diagram of the experiment is shown in Figure 4.

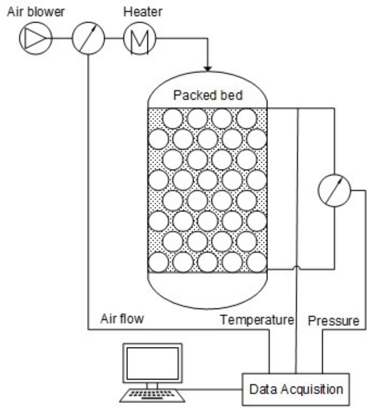

Figure 4. Schematic diagram of the ARIANE experiment [5]

The airflow is controlled to a constant value and is heated by a heater before entering the packed bed so that the axial temperature within the packed bed can be measured. The parameters given by the reference of the experiment and the design parameters set in GAMMA+ are shown in Tables 2 and 3.

Table 2. Input parameters for modeling of packed bed [5]

parameters		value	unit
Working fluid		Air	
Storage material		Rock	
Inlet	Pressure	150	kPa
	Temperature	550	°C
	Mass flow rate	0.004	kg/s
Geometry	Inner Diameter	0.150	m
	Height	1.20	m
	Rock Diameter	0.02	m
	porosity	0.4	
Rock	Thermal conductivity	2.5	W/mK
	Density	2800	kg/m^3

Table 3. Design parameters for modeling of packed bed

parameters		value	unit
Nodes	Fluid and Wall	7×20	(r,z) cell
Ambient	Pressure	101	kPa
	Temperature	20	°C
Geometry	structure	Double wall	
	wall material	SUS304	
	thickness	10	mm
	Outer Diameter	0.290	m
Rock	emissivity	0.8	
Insulation	material	Foam	
	Thermal conductivity	0.001	W/mK
	thickness	50	mm

The following is the result of a 2-hour simulation, where the circle marker is the value of the experiment and the line is plotted by interpolation of the GAMMA results.

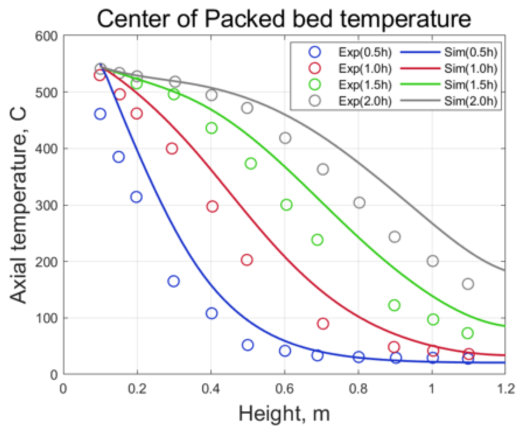

Fig 5. Rock temperature of Center of Packed bed temperature at height (HTC: 0.01 W/m^{2}K)

The simulation results are shown in Table 4 for more detailed values and are in good agreement with the experimental values from ARIANE TEST [5]. However, since the simulation results are higher than the experimental values at longer storage times(charging), it can be assumed that the heat loss to the outside is not sufficiently simulated. Therefore, the convection and radiation heat transfer coefficients of the ambient air have been adjusted and compared.

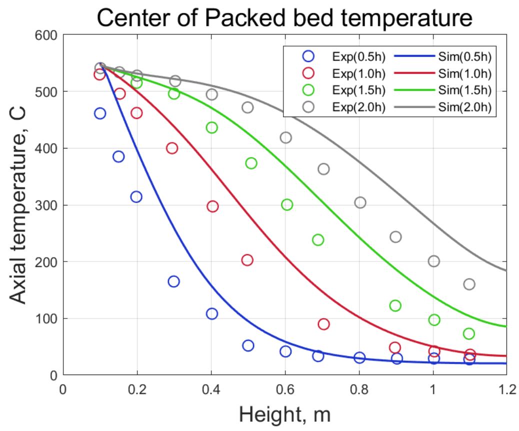

Fig 6. Rock temperature of Center of Packed bed temperature at height (HTC: 1.0W/m^{2}K)

The boundary of the wall can be set as the heat loss to the environment, where the wall has a constant convective heat transfer coefficient and radiation to the environment. According to Table 1, the constant heat transfer coefficient (W/m^{2}K) and ambient temperature of the east boundary of the wall can be designed using the GAMMA+ code.

Table 4. Inlet and Outlet temperature of the layer of rocks for simulation time and Heat transfer coefficient with ambient

Simulation time	Temp	HTC with ambient	
		0.01 htc	1.0 htc
0.5 hour	Inlet	526.14	526.03
	Outlet	20.78	20.76
1.0 hour	Inlet	539.46	539.31
	Outlet	33.87	33.83
1.5 hour	Inlet	542.23	541.81
	Outlet	85.53	85.42
2.0 hour	Inlet	542.84	542.34
	Outlet	183.68	182.73

As the ambient HTC (heat transfer coefficient) increases, the rock temperature decreases slightly at the inlet and outlet temperatures for each storage time. However, there are several uncertainties on the temperature measurements in the ARIANE experiment. It is unclear where the temperature is being measured in the radial direction inside the packed bed. In addition, as the packed bed in GAMMA+ is divided into 20 axial nodes of 1.2 m, the number of axial nodes can be too small, so the temperature measurement may be uncertain due to the error in the height position. However, as shown in the results, the temperature profile is very similar indicating that it is still possible to simulate a thermal energy storage packed bed with GAMMA+.

3. Conclusion and Further works

In this study, the authors simulated the heat energy stored in packed bed using a Korean system analysis code called GAMMA+. The authors compared the results of the ARIANE experiment with the GAMMA+ simulations. The comparative analysis revealed a similarity in the temperature trends between the two sets of data. This agreement validates the feasibility of using GAMMA+ to simulate packed bed thermal energy storage systems.

As a result, the authors are encouraged by the ability of GAMMA+ to model such systems more accurately. For future research efforts, the authors intend to further solidify this conclusion by comparing experimental results under different conditions with GAMMA+ simulations. This will further enhance the use of GAMMA+ for the design of systems combining packed beds, thereby contributing to the advancement of thermal energy storage technologies.

ACKNOWLEDGEMENT

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NOMENCLATURE

ε_r	*pebble emissivity*
d_p	*pebble diameter*
λ_f	*thermal conductivity of fluid*
λ_s	*thermal conductivity of solid*
μ_p	Poisson ration
E_s	Young's modulus
P_e	*External pressure estimated by the weight of particles*

$$S = S_F = 1$$

$$N_L = \frac{1}{d_p}$$

$$N_A = (N_L)^2$$