Packed bed thermal energy storage for nuclear power plant

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1. Introduction

A Small Modular Reactor (SMR) is an advanced nuclear reactor having power capacity up to 300MWe per unit, which is less than one-third of the generating capacity of traditional large nuclear power reactors. An SMR becomes attractive due to its practical advantages: flexible site location, improved safety, and potentially better economy [1]. To improve usage of an SMR, co-generating hydrogen, desalination, heat storage, and integration with renewable energy with SMR are being researched [2].

Many studies evaluated the possibility of thermal energy storage integration with a nuclear power plant. Edward et al. studied Thermal Energy Storage (TES) integration with an advanced nuclear power plant [3]. The authors presented direct integration of thermal energy storage system with a nuclear reactor core. Carlson et al. suggested TES integrated with a steam Rankine cycle of a conventional nuclear power plant [4]. The results showed that thermal power of nuclear reactor can be maintained at constant level while heat is stored in the TES. The authors investigated several steam bypass points, and it is shown that the capacity factor of nuclear power plant can be increased up to 9.8%.

Traditionally, TES using fluid heat storage is widely studied. However, packed bed is recently spotlighted as a promising option with its practical advantages: compactness, high effectiveness, and easy manufacturing [5]. The studies on usage of packed bed with a nuclear power plant are still developing, therefore, the study for investigating feasibility of packed bed storage integration is required.

The purpose of this study is to investigate the feasibility of using packed bed storage for a nuclear power plant and also evaluating the thermodynamic performance of a packed bed storage. By developing a mathematical model of the packed bed storage, the heat transfer behavior inside of the packed bed storage is investigated. Moreover, the maximum allowable time to store nuclear heat will be discussed.

2. Methodology

In this section, a schematic diagram of steam Rankine cycle with a packed bed storage is described and the modeling method of the packed bed thermal energy storage is introduced.

2.1 System description

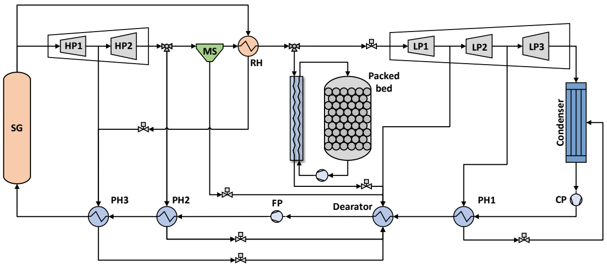

Fig. 1. Schematic diagram of steam Rankine cycle with packed bed thermal energy storage

Fig. 1 illustrates the schematic diagram of a steam Rankine cycle with a packed bed thermal energy storage. The entire layout is almost the same with a conventional nuclear steam Rankine cycle. The only difference is that the packed bed thermal energy storage is connected to the steam Rankine cycle. When load-following operation is required, steam is bypassed before low pressure turbine and heat is transferred to thermal oil (therminol VP1) in a heat exchanger. The thermal oil is used because of its large operating range, stability, and usable at ambient pressure condition. The thermal oil then transfers heat to the packed bed storage. For the packed bed side, Exhausted steam is fed into deaerator to maintain the mass flow rate of the feedwater line. The stored heat can be used in various ways: district heating or heat source for other power cycle. In this study, only charging performance is considered. The inlet condition of the steam is referred from the previous literature [6] and listed below.

Table 1: Thermodynamic conditions of inlet steam

Properties	Value	Unit
Fluid	steam	
Temperature	300	°C
Pressure	1.46	MPa
Mass flow rate	37.8	Kg/sec

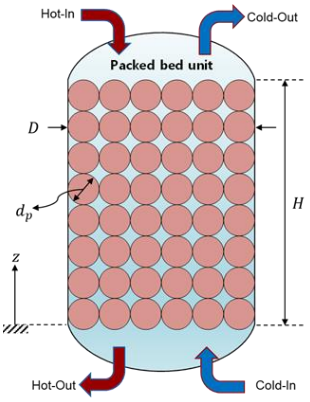

Fig. 2. Schematic diagram of packed bed thermal energy storage

Fig. 2 presents the packed bed thermal energy storage. Basically, packed bed storage consists of many numbers of solid particles. H and D represent the total height and total diameter of the packed bed respectively. Solid particles are uniformly aligned. ε represents the porosity of the packed bed and porosity is defined by the specific equation between total diameter to particle diameter (d_p). Initially, packed bed is in a certain state. When working fluid is passed through the packed bed, heat is exchanged between fluid and particles via convective heat transfer. Also, conduction heat transfer occurs between particles to particles. Even though the heat exchanging process is quite complex, the packed bed storage allows good heat transfer. The modeling method of the packed bed thermal energy storage is discussed in section 2.2.

2.2 Modeling of packed bed thermal energy storage

For calculating the heat transfer of packed bed storage, the energy balance equation is used. The packed bed storage is considered as a 1D cylindrical tank. Three assumptions are applied to simplify the packed bed modelling. Eqs. (1) to (3) are solved for the simulation:

1) The radiation heat transfer is neglected.
2) The porosity is uniform along the packed bed tank.
3) The particles are of the same size and spherical shape.

$$\varepsilon\rho_f c_{p.f}\left(\frac{\partial T}{\partial t}+u_f\frac{\partial T}{\partial z}\right)=\varepsilon k_f\frac{\partial^2 T_f}{\partial z^2}+\frac{6(1-\varepsilon)}{d_p}h_{fp}\left(T_s-T_f\right)+h_w\left(T_w-T_f\right) \qquad (1)$$

$$(1-\varepsilon)\rho_s c_{p.s}\frac{\partial T_s}{\partial t}=(1-\varepsilon)k_s\frac{\partial^2 T_s}{\partial z^2}+\frac{6(1-\varepsilon)}{d_p}h_{fp}\left(T_f-T_s\right) \qquad (2)$$

$$\rho_p c_{p.p}\frac{\partial T_p}{\partial t}=k_p\left(\frac{\partial^2 T_p}{\partial r^2}+\frac{1}{r}\frac{\partial T_p}{\partial r}\right) \qquad (3)$$

where ε is the porosity of the packed bed, ρ is density, c_p is the specific heat of fluid, k is thermal conductivity, d_p is particle diameter, h_{fp} is the heat transfer coefficient of fluid to solid, h_w is the heat transfer coefficient of heat loss to ambient, and T is temperature. Subscripts f, p, and s are fluid, particle, and solid, respectively.

In order to calculate heat transfer between fluid and solid, an empirical correlation is used. For the Nusselt number, the following correlation is used [7].

$$Nu=\frac{h_{fp}d_p}{k_f}=2+1.1Pr^{\frac{1}{3}}Re_p^{0.6} \qquad (4)$$

To solve the energy balance equation, boundary conditions and initial conditions have to be specified for the fluid and the solid.

$$T_f(z=0)=T_{in};\ \frac{\partial T_f}{\partial z}(z=H)=0 \qquad (5)$$

$$T_s(z=0)=T_{in};\ \frac{\partial T_s}{\partial z}(z=H)=0 \qquad (6)$$

$$T_f(t=0)=T_{in};T_s(t=0)=T_o \qquad (7)$$

$$\frac{\partial \mathrm{T_p}}{\partial r}(r=0)=0;\ T_p\left(r=\frac{R}{2}\right)=T_s \qquad (8)$$

where T_{in} is packed bed inlet temperature, T_o is initial temperature, and T_s is solid temperature.

For calculating the porosity of the packed bed, the following empirical correlations are used. The heat loss to the ambient is calculated based on the overall heat transfer coefficient from the inner to the outer wall. The inner convective heat transfer coefficient defined by Beek [8] is used in this study.

$$\varepsilon=0.375+0.17\frac{d_p}{D}+0.39\left(\frac{d_p}{D}\right)^2 \qquad (9)$$

$$\frac{1}{U_w}=\frac{1}{h_i}+\frac{D}{2}\sum_{j=1}^{m}\frac{1}{k_j}ln\left(\frac{d_{j+1}}{d_j}\right) \qquad (10)$$

$$h_i=\frac{k_f}{d_p}\left[\left(0.203Pr^{\frac{1}{3}}Re_p^{\frac{1}{3}}\right)+\left(0.220Pr^{0.4}Re_p^{0.8}\right)\right] \qquad (11)$$

In this study, granite pebble is used for the packed bed. Granite is most commonly distributed rock in S. Korea. The specific heat and density of granite are large, therefore, the required mass and volume can be minimized as well as the cost to provide the storage materials. The geometry of the granite pebble packed bed is summarized in Table 2.

Table 2: Summary of granite pebble packed bed

Properties	Value
Total Height	2.7m
Total diameter	1.35m
Pebble diameter	20mm
Porosity	0.38
Density	2500kg/m^3
Specific heat	1068J/kg-K
Axial node	300
Radial node	10

3. Results and discussions

In this section, the validation of the developed packed bed model is presented and the storage performance is discussed.

3.1 Validation of developed packed bed model

Based on the mathematical model of a packed bed storage, validation of the developed model is conducted. Meier et al. conducted experimental study of packed bed storage system [9]. The authors investigated the use of a packed bed of rocks as sensible heat storing material. The air is used as a heat transfer fluid to transfer heat into rock packed bed. The diameter of the rock bed is 0.15m and the height is 1.2m. The particle diameter is 0.02m and inlet mass flow rate of air is 4g/sec.

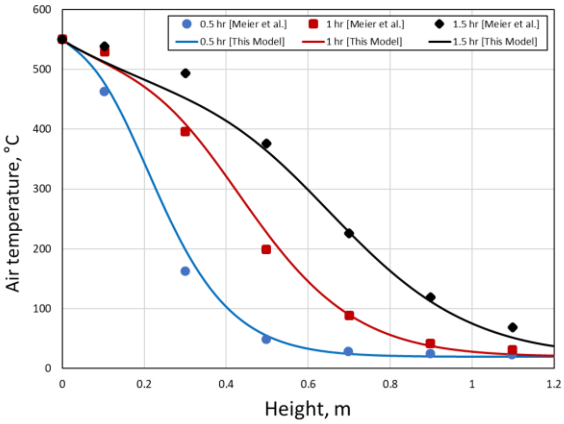

Fig. 3. Comparison of the developed model with experimental results

Fig. 3 shows the comparison of the developed model with experimental results presented in the reference. As shown in Fig. 3, the developed model well predicts the heat transfer behavior inside of a packed bed. The Mean Absolute Percentage Error (MAPE) is less than 3%.

3.2 Thermodynamic performance of the packed bed storage

The thermodynamic performance of the packed bed storage is evaluated. Before calculating heat transfer behavior inside of the packed bed, the mass flow rate of therminol VP1 is determined firstly.

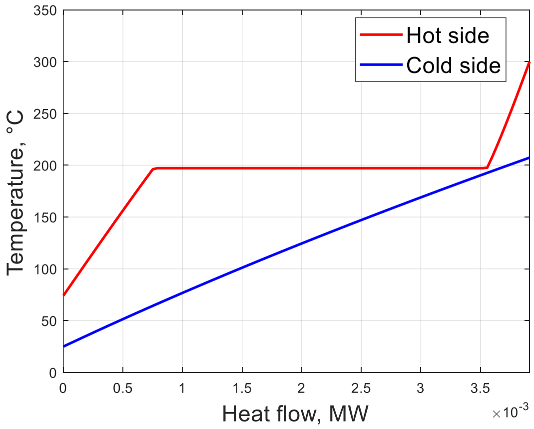

Fig. 4. Temperature distribution inside of the steam-oil heat exchanger

Fig. 4 shows the fluid temperature distribution of the steam-oil heat exchanger. The target temperature of the steam is the same with the temperature of the deaerator. To match the temperature, the mass flow rate of the therminol VP1 is calculated and reported below.

Table 3: Thermodynamic conditions of steam and VP1

Properties	Value
Steam inlet T and P	300°C (1.46MPa)
Water outlet T and P	74.1°C (1.43MPa)
VP1 inlet T and P	25°C (0.2MPa)
VP1 outlet T and P	207.3°C (0.1MPa)
Steam mass flow rate	37.8 kg/sec
VP1 mass flow rate	311.6 kg/sec

Based on the obtained results, the thermodynamic performance of the packed bed is calculated.

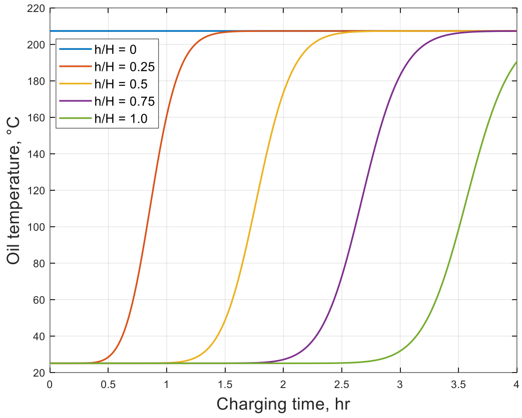

Fig. 5. Temperature distribution of therminol VP1 at each height with respect to charging time

Fig. 5. shows the change of thermal oil temperature in each axial location with respect to charging time. As seen in Fig. 5, the temperature increases slowly from the inlet to the outlet of the packed bed. The outlet temperature (green line) is maintained as constant for 3 hours and increases rapidly after. Since heat is already transferred from the inlet, it takes a long time for the heat to be transferred to the outlet. Therefore, steam can be condensed steadily for a few hours leading to steady heat storage.

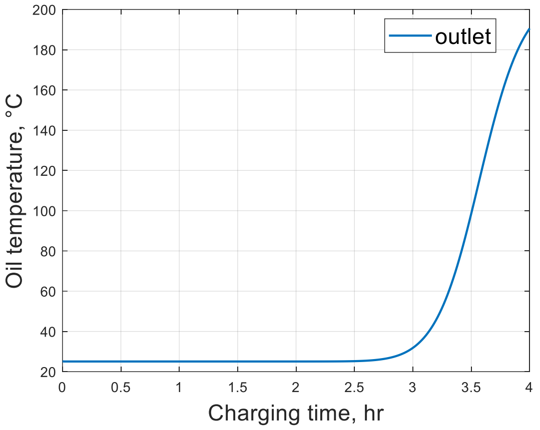

Fig. 6. Outlet temperature of the therminol VP1 with respect to charging time

As shown in Fig. 6, the outlet temperature of VP1 is maintained at initial condition for 3 hours. It means that the condensation of steam will steadily occur. After 3 hours, the packed bed is fully charged, which means that there is no space to store heat.

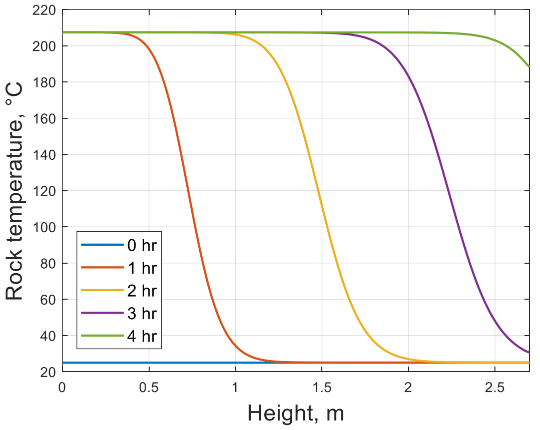

Fig. 7. Rock temperature at each time with respect to height

Fig. 7 shows the temperature of the rock inside of the packed bed. After 3 hours, the whole packed bed is fully charged. Therefore, the internal temperature the packed bed is close to uniform with respect to height. After 3 hours, the packed bed should release its heat to other heat application for the next heat storage. The maximum stored energy density of packed bed storage is calculated and listed below.

Table 4: Thermal energy storage performance of packed bed

Properties	Value
Packed bed volume	3.86m^3
Charging time	3 hours
$\dot{Q}_{oil}$	103.3MWth
Energy density	80.2MWh/m^3

4. Summary and Conclusions

The thermodynamic performance of a packed bed thermal energy storage coupled with a nuclear power plant is evaluated in this study. To evaluate heat transfer of the packed bed, a mathematical model of heat transfer between fluid to solid and solid to solid is newly developed. The validation is conducted with experimental results and it shows reasonable agreement. By using the developed model, the thermodynamic performance of the packed bed with therminol VP1 is evaluated. From the assumed geometry of the packed bed, the outlet temperature of VP1 is maintained for 3 hours. After 3 hours, the packed bed should release its heat to other heat application. When considering 3 hours charging time, the maximum energy density of packed bed storage is calculated as 80.2MWh/m^3.

This study shows the possibility of using granite rock packed bed storage for the thermal energy storage of a nuclear power plant. In the future, the whole thermodynamic performance of the steam Rankine cycle coupled with the proposed packed bed storage will be investigated.

5. Acknowledgment

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