Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Investigation on Thermal Behavior of Thermocline Thermal Energy Storage Based on Operation Scenarios

J. W. Han and B. J. Chung*
Department of Nuclear Engineering, Kyung Hee University
#1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do, 17104, Republic of Korea
**Corresponding author: bjchung@khu.ac.kr*

***Keywords :** Thermal energy storage, thermocline, packed bed, operation scenario, operation strategy

1. Introduction

With the increasing integration of renewable energy into electric grid systems, issues of energy intermittency have emerged due to inherent limitations of renewable sources, such as variability due to weather conditions [1,2]. Consequently, the development of technologies aimed at enhancing grid stability, such as energy storage becomes crucial.

In numerous countries, Nuclear Power Plants (NPPs) serve as the primary sources of base-load energy. However, modifying their output to balance the variability of renewable energy sources can be challenging, even for NPPs equipped with load-following capabilities. Consequently, Thermal Energy Storage (TES) systems are being explored as a feasible approach to improve the operational flexibility of NPPs [2].

Among these, the packed bed TES system, which employs a packed bed within a storage tank, is notable. This system enables the charging and discharging of thermal energy via the heat exchange between the heat transfer fluid and the solid filler material [3].

Figure 1 shows the schematic of packed bed TES. The packed bed (TES) system is capable of creating thermal stratification within the tank. This phenomenon allows for the separation of hot and cold fluids within the same tank, enabling the discharge of hot fluid even when the tank is not fully charged. The formation of a thermocline, a distinct temperature gradient layer between hot and cold regions, plays a crucial role in the efficiency and performance of the TES system.

The current study explores the examination of a packed bed TES system using a numerical model. We conducted an analysis of the thermocline thickness and energy efficiency in various operational scenarios [4]. The objective is to understand how the thermocline's thickness changes with different TES operation situations and to propose optimal operational approaches that enhance the TES system's performance.

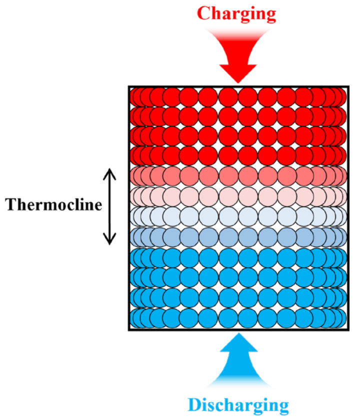

Fig. 1. Schematic of TES with packed bed geometry.

2. Present model description

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

Various numerical models have been established based on Schumann's equation to predict the thermal behavior of packed bed TES systems [5]. The term '1D' refers to a one-dimensional flow direction and '2P' indicates distinct fluid and solid temperatures. The 1D-2P model utilized in this study incorporates additional heat transfer phenomena beyond Schumann's equation, such as heat conduction between the heat transfer fluid and the solid filler. The model is predicated on the following assumptions:

I. A uniform flow is imposed at the tank inlet and outlet
II. Solid filler is considered a continuous porous medium.
III. The properties of heat transfer fluid and solid filler are independent of the temperature.
IV. TES tank is well insulated

This numerical model is governed by energy balance equations (1) and (2) for the fluid (*f*) and the solid (*s*) respectively:

Energy balance for fluid, *f*:

$$\varepsilon \rho_f C_{p,f} \frac{\partial T_f}{\partial t} + u_{sup} \rho_f C_{p,f} \frac{\partial T_f}{\partial x} = k_f \frac{\partial^2 T_f}{\partial x^2}, \qquad (1)$$

Energy balance for solid, *s*:

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

The heat transfer coefficient, *h*, is calculated using the Nusselt number correlation by Wakao et al. [6], and a_s represents the surface factor, as expressed in equations (3) and (4) respectively:

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

$$a_s=\frac{6(1-\varepsilon)}{d_p}. \quad (4)$$

2.2 Numerical method

To predict the thermal behavior of the packed bed TES system, Eqs. (1) and (2) were numerically solved by utilizing an in-house code. The finite difference method was employed with implicit scheme. The in-house code was developed using MATLAB software.

3. Thermal energy storage integrated with nuclear power plants

3.1 Design specifications of TES

In order to assess the performance of the packed bed TES, certain design specifications were chosen. These parameters are represented in Table I. The selection of the types of heat transfer fluid and solid filler was informed by the thermal energy distribution system of the Idaho National Laboratory [7]. The temperature range utilized was based on the inlet and outlet temperatures of the secondary-side steam generator of the APR1400.

Table I: Design specifications for the present study

Design specifications of TES	
Tank height (m)	4
Tank diameter (m)	1
Solid diameter (m)	4×10^{-3}
Solid material	Alumina [7]
Heat transfer fluid	Therminol-66 [7]
Hot fluid temperature (℃)	282.2
Cold fluid temperature (℃)	232.2
Porosity	0.41
Fluid velocity (m/s)	5×10^{-3}

3.2 TES operation scenarios

In combining thermal energy storage (TES) systems with nuclear power plant, it is necessary to determine the appropriate operating time ranges for the TES.

Research by Frick et al. found that it takes about 5 to 10 minutes for a TES system to reach a stable operating condition when integrated with SMR [8]. This stabilization period should be considered for effective operation of the TES that responds to unpredictable renewable variability.

In terms of energy grid management, the grid is designed to adapt within short periods, typically ranging from 5 to 15 minutes [9]. If this time resolution is too long, it can't keep up with the fast changes of renewable energy, making the TES less useful. Also, long time resolution includes the characteristics of regional or time. As a result, the operation strategy cannot be applied effectively in certain situations. However, a shorter time resolution makes the system more general by reducing the characteristics of renewable energy in different places and times. Consequently, the operation time range of the TES is selected in a 5 to 15 minute.

Regarding the management of the energy grid, it's essential to consider how the grid is designed to adapt over time, typically within intervals of 5 to 15 minutes. If the time resolution is too lengthy, the grid struggles to keep pace with the rapid fluctuations associated with renewable energy sources, diminishing the utility of TES. Additionally, a prolonged time resolution encompasses regional characteristics or temporal aspects, rendering the operational strategy ineffective in certain scenarios. Conversely, a shorter time resolution enhances the generality by minimizing the characteristics of renewable energy's variability across different locations and times. As a result, the operational time range for the TES is strategically chosen to fall within a 5 to 15 minutes range.

In this study, we selected repetitive operations for 5, 10, and 15 minutes as TES operational scenarios. This decision was based on the consideration that the most extreme case for TES operation would be the scenario where the system undergoes periodic charging and discharging due to significant fluctuations in renewable energy. Moreover, the 5-minute scenario represents the TES operating condition that repeatedly operated without being fully charged, while the 15-minute scenario involves operation repeatedly when the TES is almost fully charged. Additionally, it is assumed that the TES is fully charged during the late-night hours when electricity demand is minimal, and the operation of the TES begins with discharging.

3.3 Thermal performance evaluation

To assess the thermal performance of TES, the concept of energy efficiency, denoted as η, is introduced. This is a common way to estimate the performance a of thermal energy storage system, and it can be described using Eq. (5) [10]

$$\eta = \frac{\int_0^{t_{dischrage}} \dot{m} C_f \left[T_{f,\mathrm{out}}(t) - T_{low} \right] dt}{\int_0^{t_{chrage}} \dot{m} C_f \left[T_{high} - T_{low} \right] dt}. \tag{5}$$

The discharging time was defined as the duration it takes for the discharging temperature to fall below a certain threshold. In this study, the threshold temperature was set to 1 K.

4. Results and discussion

4.1 Thermocline thickness variation according to scenarios

Figure 2 shows the variation in the thickness of the thermocline as a result of repetitive operations in the 5-minute operating scenario. The overall thickness of the thermocline tended to increase. The decrease in the thermocline's thickness at certain points during operation was due to the discharge of the thermocline region itself, resulting in a reduction in thickness. During TES operation, the thermocline expands as a result of heat exchange between the heat transfer fluid and the solid filler material, as well as the thermal conduction of the heat transfer fluid. After approximately 80 cycles of operation, the thickness of the thermocline becomes nearly constant. This indicates that a balance has been achieved between the thickening of the thermocline due to the operational process and its thinning due to discharge.

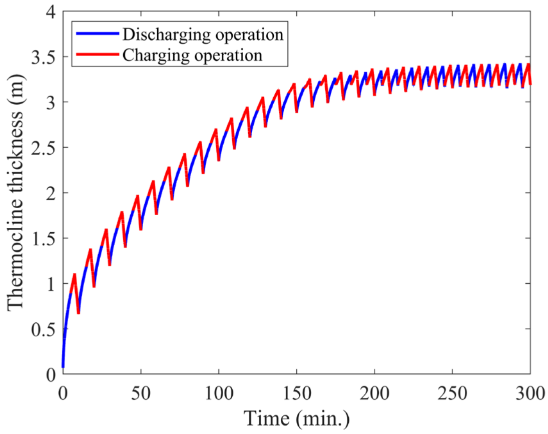

Fig. 2. Thermocline thickness variation at 5 min. scenario.

Figures 3 and 4 respectively illustrate the variations in thermocline thickness during the 10-minute and 15-minute operating scenarios. As the duration of the operation increased, the maximum thickness of the thermocline decreased. This is because longer operation cycles resulted in a larger area of the thermocline being discharged, thereby enhancing the effect of thickness reduction. Moreover, the increase in operation duration led to a reduction in the number of cycles required for the thermocline thickness to achieve its saturation level. To effectively utilize TES in responding to the variability of renewable energy, it is advantageous to use operation cycles that match the capacity of the TES. However, due to the irregular variability of renewable energy, analysis of various operating conditions remains essential.

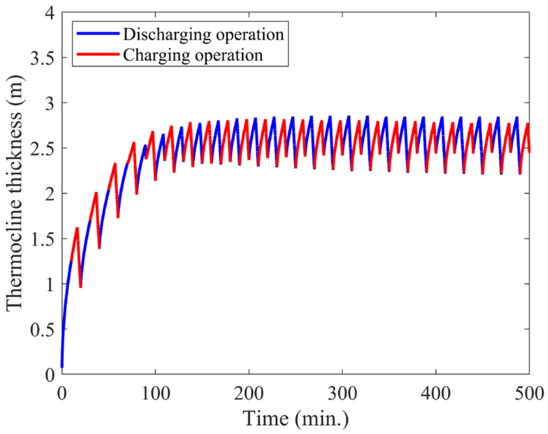

Fig. 3. Thermocline thickness variation at 10 min. scenario.

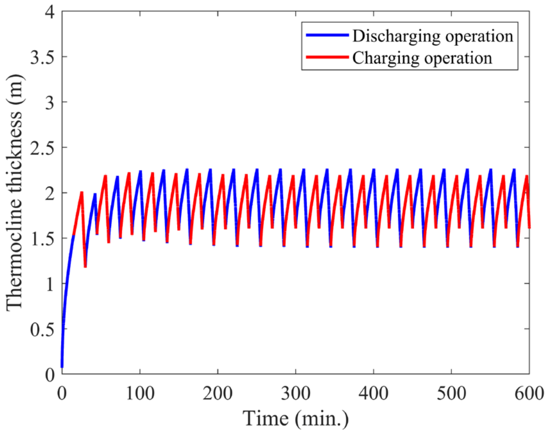

Fig. 4. Thermocline thickness variation at 15 min. scenario.

4.2 Energy efficiency variation according to scenarios

Figure 5 presents a graph calculating the energy efficiency per cycle, with one cycle defined as one charging and one discharging, across different operating scenarios. Energy efficiency was calculated according to Eq (5). In all operating scenarios, energy efficiency decreased as the number of cycles increased. The reason for this decrease, as observed in Section 4.1, is due to the increase in the thickness of the thermocline during the TES operation. A thicker thermocline reduces the high-temperature region within the TES, leading to lower energy efficiency. The graph illustrates a trend of decreasing energy efficiency until it reaches a saturation point, mirroring the behavior observed in the thermocline's thickness, which becomes saturated over repeated cycles. Consequently, the continuous and repetitive use of the Thermal Energy Storage (TES) system negatively impacts its energy efficiency.

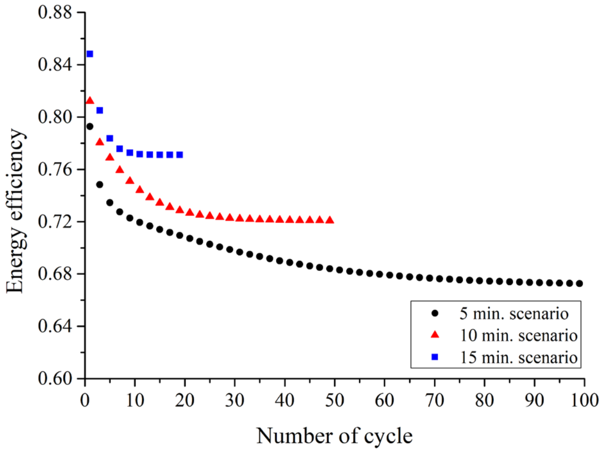

Fig. 5. Variation of energy efficiency according to cycle operation.

5. Conclusions

We carried out a performance evaluation based on operation scenarios for the packed bed thermocline thermal energy storage (TES) system. Our benchmark was previous research that had selected foundational scenarios integrating TES with nuclear power, and we analyzed the thermal behavior within the TES according to these scenarios. We employed an in-house code to solve the mathematical model numerically, and we calculated energy efficiency as an indicator for performance evaluation. The thermocline thickness continued to increase during the charging or discharging operations, and it reached a saturation point with repeated operations. Energy efficiency was found to be higher when the system operated for a duration matching the TES capacity. However, as the cycle operation was repeated, energy efficiency decreased. The Authors anticipate that this study will serve as a fundamental guideline for establishing operating scenarios.

ACKNOWLEDEGEMENT

This work was supported by the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Ministry of Trade, Industry and Energy, Republic of Korea (No. RS-2023-00244330).

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, “valuation 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] P. Romanos, A.A. Kindy, A.M. Pantaleo, C.N. Markides, Flexible nuclear plants with thermal energy storage and secondary power cycles: Virtual power plant integration in a UK energy system case study, e-Prime – Advances in Electrical Engineering, Electronics and Energy, Vol.2, 100027 2022.

[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] 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.

[8] K. Frick, Modeling and Design of a Sensible Heat Thermal Energy Storage System for Small Modular Reactors, Doctor of Philosophy thesis, 2018.

[9] F. P. M. Kreuwel, W. H. Knap, L. R. Visser, W. G. J. H. M. van Sark, J. V. G. Arellano, C. C. van Heerwaarden, Analysis of high frequency photovoltaic solar energy fluctuations, Solar Energy, Vol.206, pp.381–389, 2020.

[10] 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.