Performance Analysis of Thermal Energy Storage System For Nuclear Power Plant Application

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1. Introduction

A low-carbon power generation technology is important to mitigate climate crisis. In particular, the share of renewable energy such as solar and wind energy is increasing significantly. Technically, one of the most challenging problems is alleviating renewable energy intermittency issue. Power supply and demand cannot be completely matched under all circumstances. As such, the increase in the proportion of renewable energy causes challenges to electricity grid systems [1].

Energy storage system (ESS) can stabilize grid system and make it more efficient [2]. Recently, thermal energy storage system (TES) has been studied for nuclear power plant (NPP) application in several previous studies [3-5]. TES is easy to integrate with NPP because both direct heating and electrical heating are possible. For directly heating, the TES temperature is determined by the operating temperature of the NPP. The operating temperatures vary from conventional NPP (Pressurized water reactor (PWR)) to Generation IV (Gen-IV) reactors (Sodium-cooled fast reactor (SFR), Molten salt reactor (MSR), etc.). It is important to select a suitable heat transfer fluid (HTF). Indices for evaluating the performance of ESS are round-trip efficiency (RTE) and energy density. Therefore, in this study, TES performance is analyzed for NPP application. The efficiency of the TES dedicated power cycle and the energy density of the TES are discussed at different temperatures.

2. TES integrated NPP

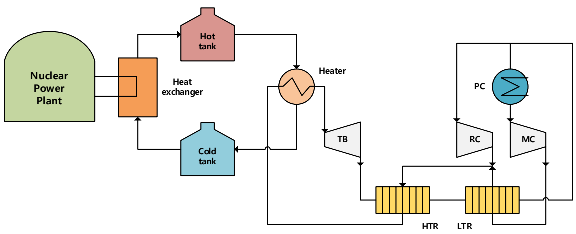

Fig. 1. TES integrated NPP

A configuration of TES integrated NPP is shown in Fig. 1. TES can be integrated to both primary and secondary sides of NPP. Since this study focuses on the selection of suitable HTF and the performance of TES dedicated power cycle at operating temperature of NPP, the direct location of the integration is not the main subject.

TES operates in two modes: charging mode and discharging mode. During charging mode, thermal energy of NPP transfers to TES. HTF is heated in a heat exchanger and stored in the hot tank. When additional power is required, thermal energy is converted to electric energy using TES dedicated power cycle. Generally, round-trip efficiency is defined as the ratio of the power that can be produced directly without storing heat to TES and the power that can be produced by receiving heat from TES after storage [6]. However, in this study, since the power cycle of NPP is not known, only the performance of the TES dedicated power cycle is analyzed.

The purpose of TES is to store the transferred heat without reduction in temperature [7]. This is because temperature decrease causes reduction in efficiency when converting thermal energy to electric energy. Most of the currently installed TES are two tanks. The two tank TES is the most efficient TES for an ideal situation without temperature decreases. The main HTF used in power plant industry are HITEC salt and solar salt [8]. However, both of these salt mixtures become thermally and chemically unstable at temperatures above 600˚C. Thus, liquid sodium was recommended as HTF at higher temperature [9].

Table. 1. Properties of HTFs [8, 9]

HITEC salt	
Operating temperature [˚C]	142 ~ 538
Density $[kg/m^3]$	$\rho = 2293.6 - 0.7497T$
Heat capacity $[J/(kg\ K)]$	$C_p = 5806 - 10.833T + 7.2413 \times 10^{-3}T^2$
Solar salt	
Operating temperature [˚C]	223 ~ 550
Density $[kg/m^3]$	$\rho = 2263.628 - 0.636T$
Heat capacity $[J/(kg\ K)]$	$C_p = 1396.044 + 0.172T$
Liquid sodium	
Operating temperature [˚C]	97.7 ~ 873
Density $[kg/m^3]$	$\rho = 219 + 275.32 \times \left(1 - \frac{T}{2503.7}\right) + 511.58 \times \left(1 - \frac{T}{2503.7}\right)^{0.5}$
Heat capacity $[J/(kg\ K)]$	$C_p = (1.6582 - 8.4790 \times 10^{-4}T + 4.4541 \times 10^{-7}T^2 - 2992.6T^{-2}) \times 10^3$

The S-CO_2 power cycle has higher efficiency than that of the steam Rankine cycle for the same turbine inlet temperature (TIT). Also, sodium does not react with S-CO_2 violently [10]. Thus, the S-CO_2 power cycle is adopted as TES dedicated power cycle. Since it operates above the critical point, the pressure ratio is small and the turbine outlet temperature is high. The S-CO_2 power cycle requires a large amount of recuperation process to increase the efficiency. The S-CO_2 recompression cycle has high cycle efficiency and is mainly used to avoid the pinch point problem in the recuperators. The conditions of TES dedicated S-CO_2 recompression cycle are summarized in Table. II. Main compressor inlet pressure (MCIP) and split ratio are optimized through the power cycle thermodynamic analysis code to achieve the maximum efficiency with respect to TIT. The split ratio is defined as the ratio of the main stream and MC split stream.

Table II. S-CO_2 recompression cycle conditions

Parameters	Value
Turbine efficiency [%]	90
Compressor efficiency [%]	80
Heat exchanger effectiveness [%]	90
Heat exchanger pressure drop [%]	1
Main compressor outlet pressure [MPa]	25
Main compressor inlet temperature [$^\circ$C]	35
Net work [MW]	10
Turbine inlet temperature [$^\circ$C]	Variable
Main Compressor inlet pressure [MPa]	Variable
Split ratio	Variable

KAIST-CO_2 Cycle Design (CCD) is a code that can analyze the cycle performance at the design point through thermodynamic analysis. This code loads properties from REFPROP of NIST and is developed under MATLAB environment. The developed code was validated and verified from the previous studies [11]. TIT, MCIP and split ratio are used as input values and HTR cold side inlet temperature is assumed first. Each component is calculated based on the values summarized in Table II and the component models. Finally, the convergence error of HTR cold side inlet temperature is checked. After calculating the power cycle, the cold tank temperature and mass flow rate of HTF are determined to satisfy the heat exchanger effectiveness conditions based on the heater inlet and outlet conditions of power cycle. Fig. 2 shows the efficiency of TES dedicated power cycle. Roughly, the RTE can be defined as the ratio of the efficiency of the NPP to the efficiency of the TES dedicated power cycle. Therefore, the S-CO_2 recompression cycle with high efficiency is promising as a TES dedicated power cycle.

Energy density is defined as the amount of energy that can be produced per volume. Since the two tank TES is adopted in this study, energy density is calculated with equation (1) [12]. The mass flow rate and time in charging mode and discharging mode were assumed to be the same.

$$\omega = \frac{\dot{W}_{out} t_{disch}}{\frac{\dot{m}_{disch} t_{disch}}{\rho_{hot}} + \frac{\dot{m}_{ch} t_{ch}}{\rho_{cold}}} \quad (1)$$

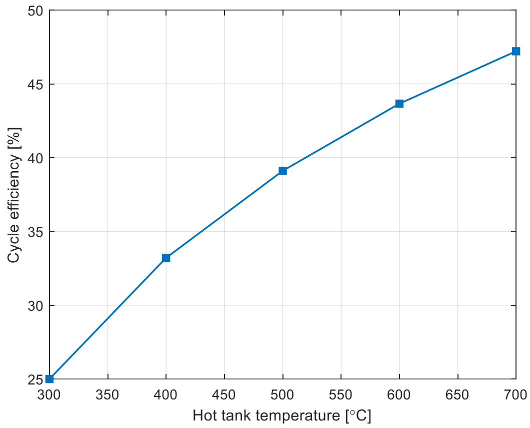

Fig. 1. TES dedicated power cycle efficiency

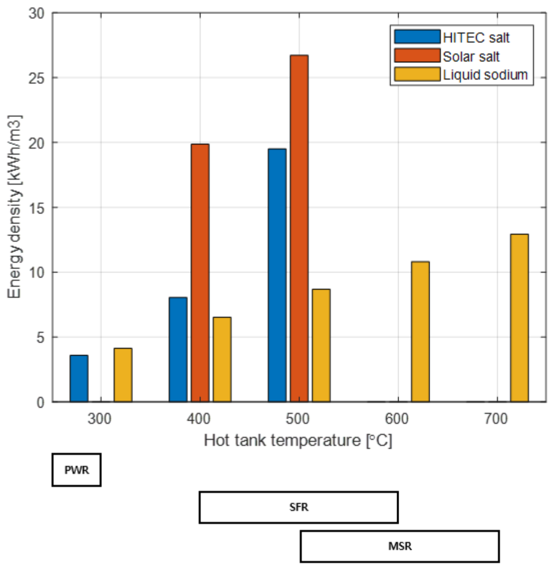

Fig. 2. TES energy density

Fig. 2 shows the TES energy density of each HTF. The temperatures where energy density values are not indicated are because the temperature of the hot tank or cold tank is outside the operating temperature range of the HTF. In the temperature range where all three HTFs can be utilized, the energy density of solar salt is overwhelmingly high. Above 600°C, only liquid sodium is possible, and the energy density is more than 10 kWh/m^3. At 300°C, the energy densities of HITEC salt and liquid sodium are almost the same. However, since the applicable nuclear power plant type is pressurized water reactor (PWR), HITEC salt is recommended due to concerns of sodium-water reaction.

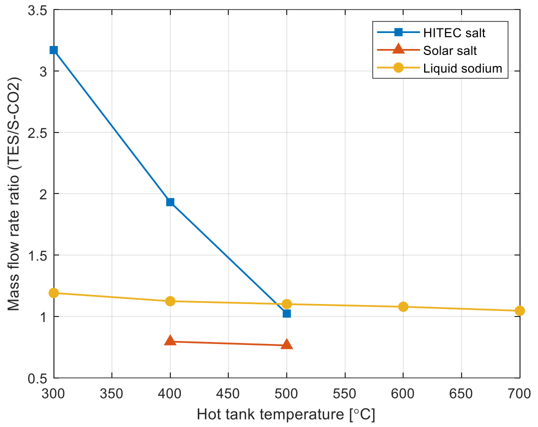

Fig. 3. Mass flow rate ratio between TES and power cycle

Fig. 3 shows the mass flow rate ratio between TES and power cycle. This ratio is the required TES mass flow rate for the same mass flow rate of power cycle. Therefore, solar salt with the smallest ratio value shows the best performance in terms of energy density. In the case of HITEC salt, as the temperature increases, the ratio value decreases rapidly, and the energy density increases rapidly. When comparing the HITEC salt and liquid sodium, the energy density of the HITEC salt is better despite higher ratio of the HITEC salt. This means that the storage capacity of HITEC salt is better than that of liquid sodium.

3. Conclusions

As interests in low carbon power generation are growing, the share of renewable energy power generation is increasing. One of the solutions to the intermittency problem of renewable energy is flexible operation of conventional power plants. Therefore, this study focused on TES integrated NPP and preliminary analysis result of TES performance for application to various types of nuclear power plants is presented.

Overall, the energy density of TES is quite comparable to the other mechanical energy storage system such as compressed air energy storage system or liquid air energy storage system. It is found that using TES is better for Gen-IV type reactors rather than coupling with conventional NPP, PWR.

Acknowledgement

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