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Simulation of the Thermal Energy Storage System (TES) in Hybrid Energy System

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1. Introduction

A hybrid energy system (HES) is being developed that combines two or more energy production systems including renewable energy, with various energy storage systems. It resolves the mismatch of the energy between supply and demand, enhances the efficiency of power utilization, and ensures the quality and safety of electricity while also improving economic feasibility.

In particular, HES utilizing small modular reactor (SMR) can reduce carbon emissions and provide various advantages such as relatively small power production, small-scale components, and modular construction. It could be constructed near an application plant independently or as a group depending on market demand. And by utilizing thermal energy storage system (TES) in HES, the system can be made more flexible by enabling short-term adjustments in buffering daily or seasonal demand fluctuations.

Thermal energy storage is one of the classical energy storage methods, providing the advantages of low cost and high round-trip efficiency. By installing thermal energy storage systems at nuclear power plants, which generate large amounts of thermal energy, the following benefits can be achieved: 1) Minimizing surplus electricity production by adjusting the electrical output of the nuclear power plant according to power demand, 2) Maintaining a constant reactor output despite fluctuations in power demand, ensuring economic operation of nuclear plants, and 3) Adding flexibility to the power grid and optimizing resource utilization through the charging and use of thermal energy.

In this study, the thermal energy storage system (TES) added to the hybrid energy configuration is conceptually designed, and correspond computational model is developed using Modelica language [1]. Through computational analysis, the thermal-hydraulic behavior of the hybrid energy system including TES and the safety impacts of the SMR are evaluated. The thermal energy storage system (TES) is added to the SMR to extract steam from the nuclear power plant during the daytime, store thermal energy, and then use it for process heat facilities to reduce the load on the electrical grid and use energy efficiently.

2. Conceptual Design of TES

2.1 Design Concept of TES

The heat source of the TES is steam extracted from the secondary side of SMR. This steam transfer heat to the TES medium, sodium (Na), through an intermediate heat exchanger (IHX) and thermal energy is stored in the heat storage tank (hot tank). The operation modes of the thermal energy storage system consist of charging mode and discharging mode. In charging mode, heat is stored, whereas in discharging mode, the stored heat is utilized.

During charging mode, sodium from the cold tank moves through the IHX and an electrical heater, transferring heat to the hot tank for storage. In discharging mode, sodium from the hot tank flows back to the cold tank while transferring heat to the process heat facility system through the IHX. Fig.1 presents the schematic drawing.

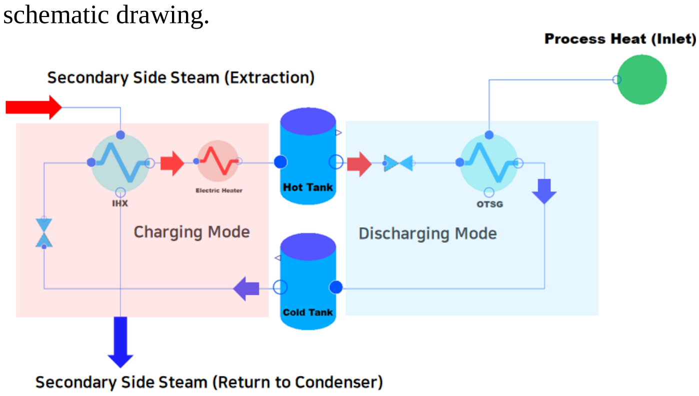

Fig.1 Schematic Drawing of TES

2.2 Sizing and Specifications of TES

The sizing of the thermal energy storage tank is conducted referred from TES of IPWR [2]. In the hybrid energy system applying TES, the SMR is adopted as SMART [3], which was developed by KAERI. A simulation model of SMART applied to the Hybrid Energy System has been previously developed, with the maximum steam extraction fraction (the ratio of steam extracted for process heat utilization to the total steam generated in the steam generator) designed as 0.1. The maximum steam extraction fraction for IPWR is 0.45

The scaling ratio is 6.25:1 for the thermal energy storage tank of the IPWR, considering the ratio of steam extraction between the IPWR and SMART as follows.

· Steam extraction rate of IPWR

: 264 kg/s × 0.45(Max. Steam Ext) = 119.12 kg/s

· Steam extraction rate of SMART

: 190.4 kg/s × 0.1 = 19.04 kg/s

The specifications of TES, including the IHX and thermal storage tank, have been determined and are shown in Table 1. The specification of the IHX is optimized based on the simulation results.

Table.1. Specification of the TES

Parameter	IPWR (Ref.)	SMART	Unit
Fluid	Therminol66	Sodium	-
Tank Vol.	226,535	36,187	m^3
IHX Vol.	101.94	16.3	m^3
IHX Tube No.	19,140	3,057	-
Tube ID.	0.013	0.005	m
Tube OD.	0.018	0.007	m
Tank Fill Gas Mass	5.24E+05	37933	kg

3. Computational Simulation

3.1 Developing Simulation Model of TES in Hybrid Energy System

The SMART-TES integrated model is developed by adding the TES model to the pre-developed SMART model using the OpenModelica platform. The integrated model is shown at Fig.2

Based on the SMART100 data, a model for a pressurized water reactor SMR was pre-developed as a component of the HES using Modelica code. Specifically, individual models for the core, RCS, once-through steam generator (OTSG), and steam power conversion system were developed, and these models were interconnected to construct the SMART100 integrated model. Additionally, based on the SMART 100 integrated model, a model was developed to extract steam from the main steam line and recover it to the secondary side feedwater line, utilizing the heat of the power plant.

At the inlet of the shell side of the TES intermediate heat exchanger, steam flows in and exchanges heat with sodium on the tube side, resulting in condensation. A heat exchanger capable of simulating this phenomenon and enthalpy are input as a function of temperature, and the filled gas at the top is applied. And to prevent the sodium from freezing, a electrical heater is added to inlet of the hot tank is developed and added to the model.

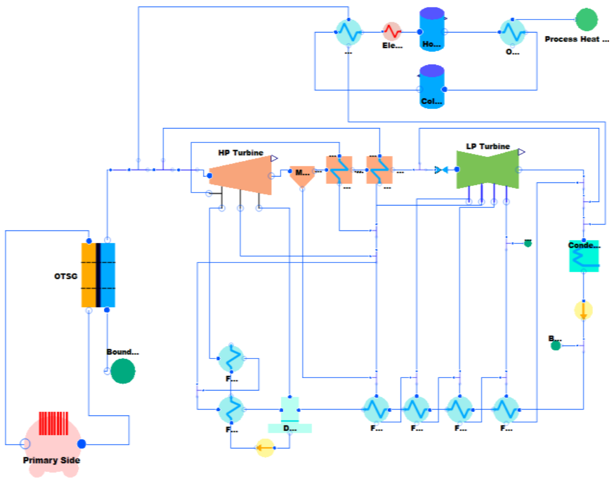

Fig.2 Schematic Drawing of SMART-TES Integrated System

3.2 Computational Simulation and Result

In the preliminary analysis using the energy storage medium therminol66, the behavior of TES is examined. In the main analysis using the energy storage medium sodium, analyses are conducted under various conditions by changing the steam extraction rate and flow rate.

(1) TES Preliminary Analysis (therminol66 medium)

The temperatures and levels of the oil in the hot tank and cold tank are examined in both charging and discharging modes. The analysis conditions are as follows.

- Steam extraction fraction : 10%
- Steam extraction point: high pressure turbine inlet
- Flow rate of oil medium (Therminol66): 30kg/s
- Initial temperature of oil
  - Charging mode: 100℃
  - Discharging mode: 180℃

In the charging mode, the oil from the low-temperature tank is heated through a heat exchanger and stored in the high-temperature tank, causing the water level in the low-temperature tank to decrease and the water level in the high-temperature tank to increase (Fig.3). The temperature of the high-temperature tank gradually rises as the flow of oil heated in the intermediate heat exchanger. The temperature of the low-temperature tank gradually drops due to heat loss (Fig.4).

In the discharging mode, the oil from the high-temperature tank is transferred to the process heat equipment through a heat exchanger and moves to the low-temperature tank. As a result, the water level in the high-temperature tank decreases while the water level in the low-temperature tank increases (Fig.5). The heat from the high-temperature tank is transferred to the process heat equipment through the heat exchanger and flows into the low-temperature tank (Fig.6).

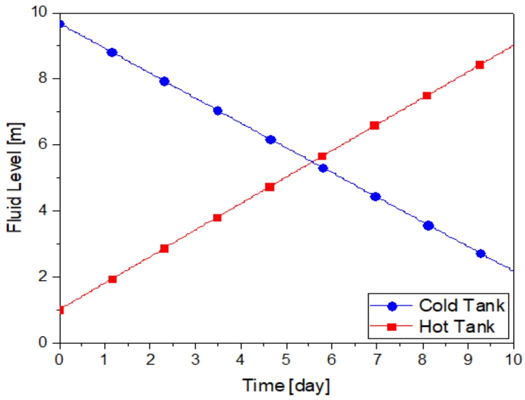

Fig.3 Tank Level in Charging Mode

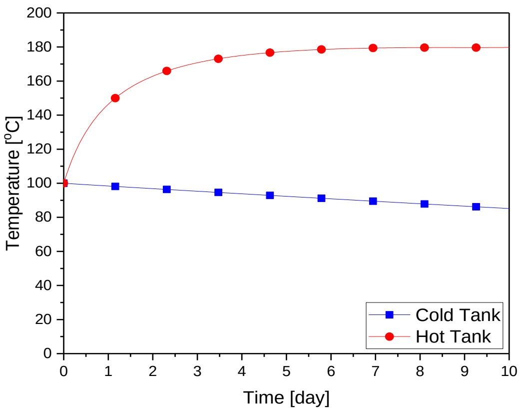

Fig.4 Tank Temperature in Charging Mode

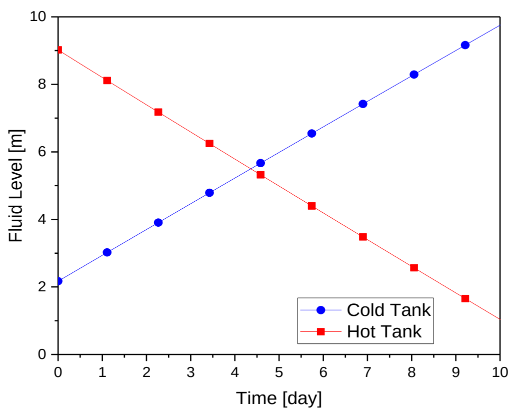

Fig.5 Tank Level in Discharging Mode

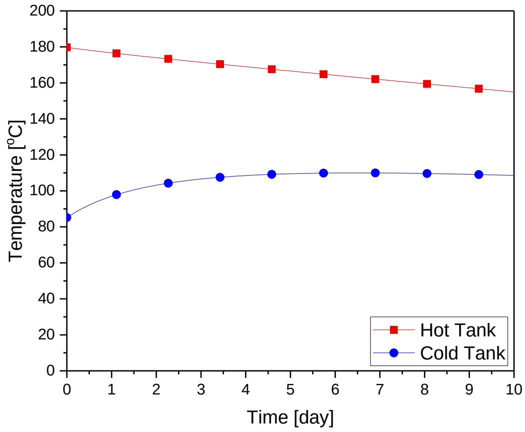

Fig.6 Tank Temperature in Discharging Mode

(2) TES Analysis (Sodium Medium)

Simulations are conducted on the operation of the thermal energy storage system under various conditions. In this case sodium is utilized as a heat storage medium. Sodium has a high boiling point, and by adding a heater, high temperatures can be utilized, making it suitable for applications such as high-temperature water electrolysis. In the charging mode, the temperature and level of the hot tank are calculated based on conditions such as steam extraction flow rate, sodium flow rate, and heater output, and the analysis results are shown in Table.2, Fig.7 and Fig.8.

Depending on the operating conditions, the sodium temperature in the hot tank ranged from 206 to 695℃. In the discharging mode, the heat (output) that can be provided to the process heat facilities is calculated based on the initial temperature of the hot tank, sodium flow rate, and the flow rate of the process heat supply. The analysis results are summarized in Table.3. Depending on the analysis conditions, the heat from electrical heater provided ranged from 0.94 to 5.86 MW.

Table.2. Analysis Result of TES Charging Mode

Charging Mode						
No.	Steam Ext. Fraction [%]	Sodium Flow Rate [kg/s]	Charging Time [s]	Heater Power [MW]	Hot Tank Temp. [℃]	Hot Tank Level [m]
1	5	5	36	0	217	8.2
2	5	5	36	3	683	9.2
3	5	10	18	0	206	8.2
4	5	10	18	3	398	8.5
5	10	5	36	0	223	8.5
6	10	5	36	3	695	8.5
7	10	10	18	0	214	9.3
8	10	10	18	3	415	8.6

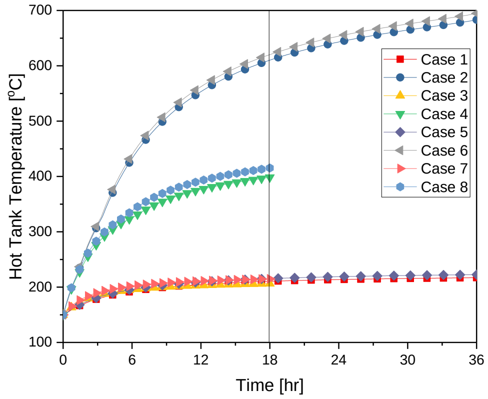

Fig.7. Hot Tank Temperature in the Charging Mode

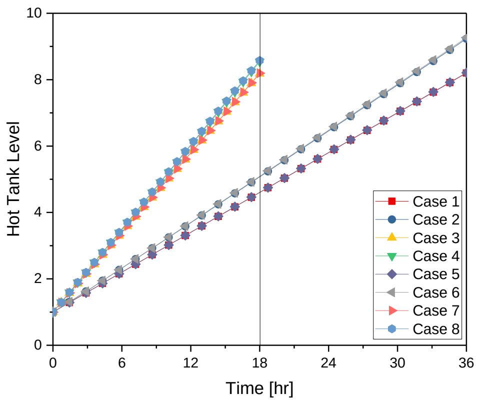

Fig.8. Hot Tank Level in the Charging Mode

Table.3. Analysis Result of TES Discharging Mode

Discharging Mode						
No.	Initial Hot Tank Temp. [℃]	Initial Hot Tank Level [m]	Sodium Flow Rate [kg/s]	Water Supply to the Process Heat Facilities [kg/s]	Hot Tank Temp. (18 hr) [℃]	Heat Supply to the Process Heat Facilities [MW]
1	694	9.3	5	2	675	2.94
2	694	9.3	5	5	675	3.31
3	694	9.3	10	2	673	4.94
4	694	9.3	10	5	673	5.86
5	206	8.2	5	2	203	0.94
6	206	8.2	5	5	203	1.18
7	206	8.2	10	2	202	1.41
8	206	8.2	10	5	202	1.90

4. Conclusions

A modeling of SMART100 based thermal energy storage system (TES), which can flexibly utilize energy, is conducted, and a computational model using OpenModelica is developed to conduct related simulations. A computational system for TES applied to SMR has been established. Through the simulation results, the temperature and flow rate that can be supplied to the process heat equipment due to steam extraction are calculated. And physical behavior of TES is verified. The model can be used in research on the multipurpose application of SMR. In the future study, the actual process heat equipment will be added to the model, and the impact on the nuclear power plant will be evaluated.

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