Development of a Dynamic Model for Integrated SMR–Thermal Energy Storage System

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1. Introduction

Recently, research on Small Modular Reactors (SMRs) has been actively conducted, with growing attention to flexible operation. Flexible operation can enhance energy quality through applications such as Thermal Energy Storage (TES), hydrogen production, cogeneration, and load-following. While conventional large-scale Nuclear Power Plants (NPPs) have primarily been operated for baseload electricity production, the importance of flexible operation is increasingly emphasized for SMRs, particularly through integration with TES system. This is because nuclear power has the potential to complement the intermittency of renewable energy sources and respond to fluctuations in electricity demand.

However, direct load-following operation at the reactor level may impact the fuel and major systems, which has led to growing interest in TES as a complementary solution [1]. Nevertheless, existing studies on the integration of SMRs with TES remain limited. In particular, research has not sufficiently addressed the constraints on extraction steam flow rate, variations in turbine output, and the quantification of storable thermal energy during the steam extraction and TES charging/discharging mode.

Furthermore, comprehensive analyses that account for actual operating conditions are lacking. This underscores the need for modeling and transient analysis to evaluate the operational characteristics of SMR–TES integrated systems.

In this study, the operational behavior of the SMR was modeled using the MARS-KS code and developed on the basis of the design data of SMART, which has received standard design approval in Korea [2, 3]. Using this model, a transient analysis framework integrating TES was established. Through this approach, the variations in extraction steam flow, turbine output, and storable thermal energy during steam extraction operation were analyzed.

2. Conceptual Design of TES System

Fig. 1 illustrates the conceptual schematic of the TES system. The main components of TES include Intermediate Heat exchanger (IHX), Hot storage tank, Cold storage tank, Once Through Steam Generator (OTSG), and Pump. In this study, liquid sodium was assumed as the storage medium for the analysis. TES can be classified into two operating modes: the charging mode, in which liquid sodium receives heat, and the discharging mode, in which it releases stored heat [4].

When TES is integrated with SMRs, steam extracted from outlet of the Steam Generator (SG) in the charging mode transfers heat to the liquid sodium through IHX. The liquid sodium is circulated from the cold storage tank to the hot storage tank by the pump, and during this process, it absorbs thermal energy from the extracted steam as it passes through the IHX. In the discharging mode, when heat release is required, the liquid sodium stored in the hot storage tank transfers its thermal energy while passing through the OTSG.

Through the storage and recovery of thermal energy, TES enhances the efficiency of power plant operations and ensures efficient performance in diverse applications such as industrial process heat supply.

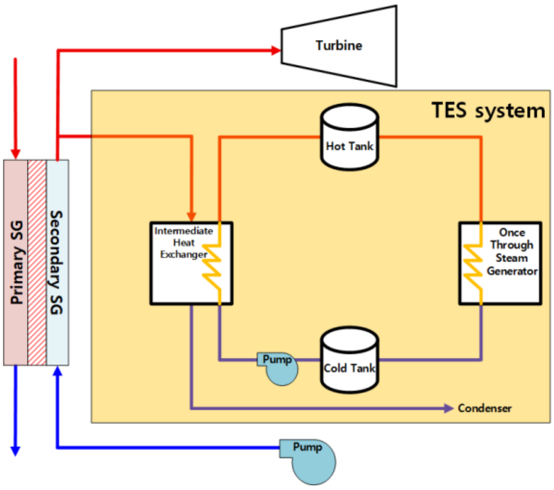


Fig. 1. The conceptual schematic of the TES system

3. MARS-KS Modeling

3.1 TES system Modeling

As shown in Fig. 2, the steam extracted from outlet of the SG enters the IHX, transferring heat to the liquid sodium through the pipe. To model this process, the extracted steam flow was assumed to pass through a header and then be divided into four parallel steam lines. Similarly, the liquid sodium pipe was also modeled as four parallel loops.

The IHX, modeled as four parallel trains, was equipped with a servo valve model to regulate the incoming flow. The servo valve model can adjust the valve position to achieve the target flow rate, and in this study, it was configured such that each train could accommodate up to 5% of the extraction flow. The extraction flow rate was considered in the range of 5–20% to evaluate the amount of thermal energy that can be stored as a function of extraction flow.

At the downstream of the IHX, two types of valves are modeled for each line: a pressure control valve and a trip valve. The pressure control valve was included to prevent a rapid temperature decrease caused by sudden pressure drops at the steam generator outlet and the extraction steam line. To ensure stable operation, the minor loss coefficient of the pressure control valve was adjusted to maintain the extraction steam header pressure at 40 bar.

The hot storage tank and the cold storage tank are connected by piping and a single junction. The pump flow was controlled using a Time Dependent Junction (TDJ) model, with the liquid sodium flow rate modeled up to 20 kg/s per train. Both the cold and hot storage tanks were modeled using pipes. The cold storage tank was modeled to maintain a constant temperature in order to prevent the solidification of liquid sodium. Sodium properties were applied in the analysis. Given its melting point of 373.5 K, and considering potential heat losses, the temperature was conservatively set at 423.15 K.

Assumptions for Key Parameters

- Steam extraction flow rate: 5–20 %
- Liquid sodium flow: 20–80 kg/s
- IHX: four parallel trains
- Heat transfer area of IHX: 360 m²
- Extraction location: outlet of the SG
- Return location: condenser

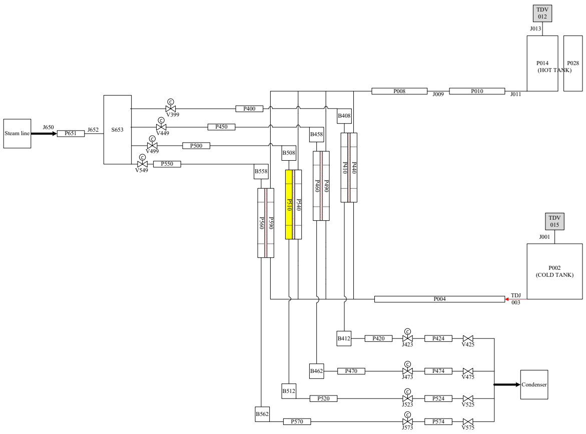


Fig. 2. Nodalization of TES System

3.2 Primary/Secondary Integrated TES Coupling Modeling

As shown in Fig.3, the previously described TES model was integrated with the primary and secondary system model based on the SMART design data. The Primary/Secondary integrated model, which had already been developed, was coupled with the TES model described in Section 3.1. For more detailed information on the Primary/Secondary integrated model, refer to Bang et al., 2024 [5].

it was assumed that a steam extraction line exists at outlet of the SG. This assumption was made to analyze how much energy could be stored under the highest energy conditions, where the extracted steam and the liquid sodium maintain a sufficient temperature difference.

Furthermore, since the purpose of this study is to evaluate the variations in turbine output and the amount of storable thermal energy when TES is coupled with SMRs depending on the extracted steam flow rate, the analysis focused on the charging mode.

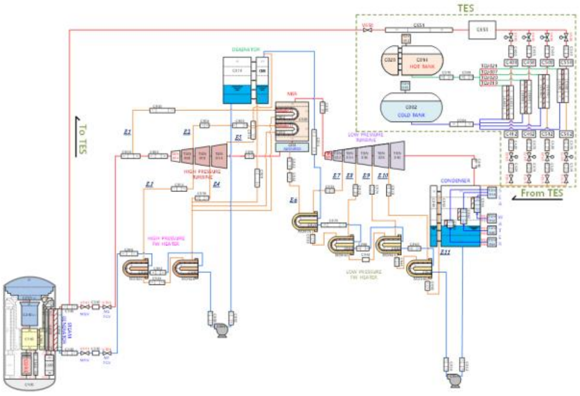


Fig. 3. Nodalization of SMR Integrated TES System

4. Analysis result of SMR-TES System

The TES integration scenarios were established as shown in Table 1, where the steam extraction flow rate was assumed to vary with time. In this scenario, the expected steam extraction demand over approximately three hours was applied to the nuclear power plant. The objective was to analyze whether the plant could stably provide the required steam and how much of the extracted thermal energy could be stored in the liquid sodium. In addition, the sodium flow rate in the loop was varied from 20 to 80 kg/s, and the analysis was performed under these different operating conditions.

Table 1: Steam extraction scenario

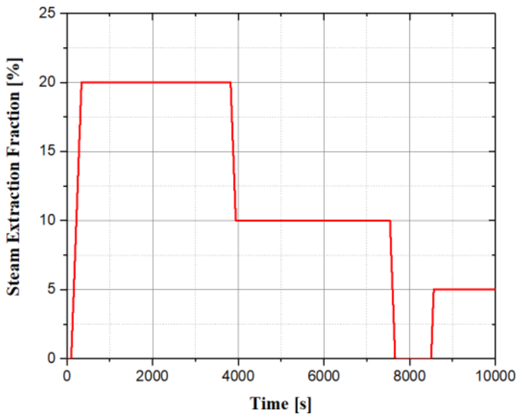
Time [sec]	Extraction rate [%]
0-360	0-20
360-3800	20
3800-4000	10-20
4000-7500	10
7500-7600	0-10
7600-8500	0
8500-8600	0-5
8600-10000	5

Fig. 5-(a) shows that the amount of steam extraction varies according to the assumed scenario, and it remains stable at each extraction level.

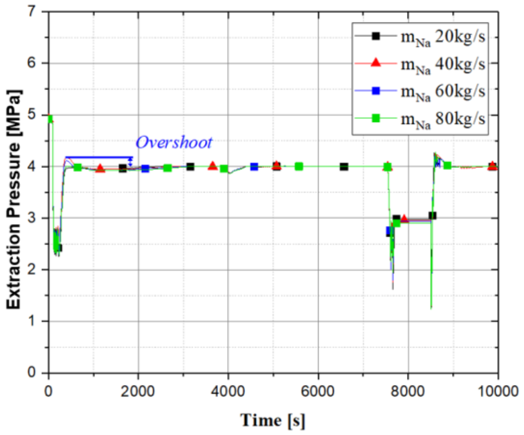
As shown in Fig. (b) and (c), the extraction line pressure required for the operation of the TES system is maintained at 40 bar, and the extraction steam flow rate is effectively controlled according to the scenario. However, overshoot and oscillations occur at the moment when the TES is activated and when the flow rate changes, but these are expected to be resolved through improvements in the control system.

Fig. 5-(d) illustrates that turbine output decreases as the amount of extracted steam increases. However, the reduction in output is slightly greater than the extraction ratio itself. This is attributed to the decrease in the mass flow rate passing through the turbine as the extraction flow increases, which causes a deviation from the design operating point. Consequently, stage efficiency degradation is expected to occur.

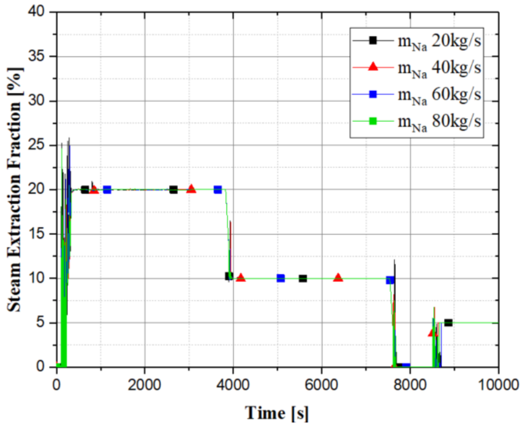
Fig. 5-(e) and (f) demonstrate that as the steam extraction flow rate increases, both the amount of energy delivered to the TES and the sodium temperature increase. It is also confirmed that a higher sodium flow rate leads to a greater quantity of storable thermal energy. Conversely, as the sodium flow rate increases, the sodium temperature decreases. at the maximum extraction flow rate of 20 %, the sodium temperature is approximately 530 K when the sodium flow rate is 20 kg/s, but decreases to about 490 K when the sodium flow rate is 80 kg/s, showing a difference of around 40 K.



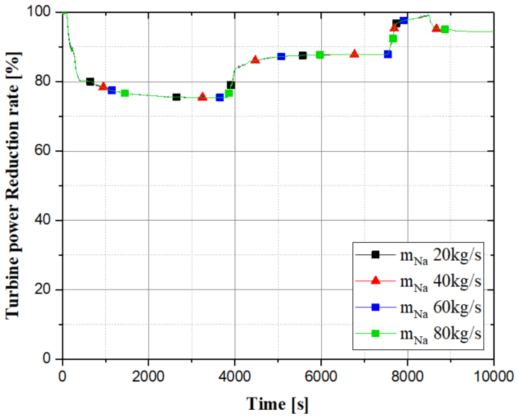
(a) TES Integration Analysis Scenarios



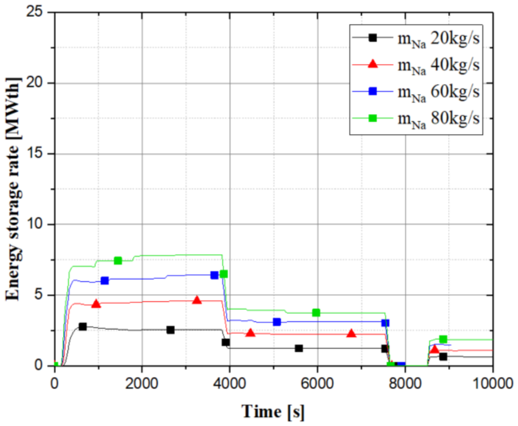
(b) Extraction Pipe Pressure



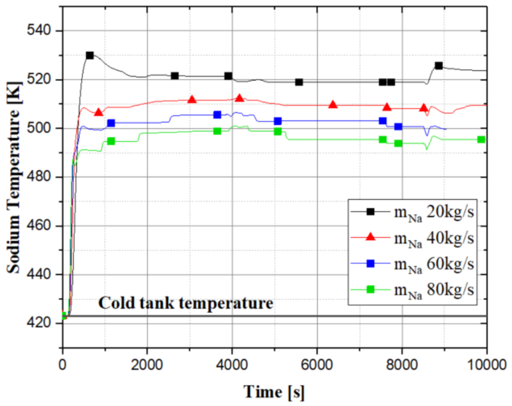
(c) Steam Extraction Mass Flow Rate



(d) Turbine Power



(e) Amount of TES energy



(f) TES Heat Exchanger inlet outlet Temperature

Fig. 5. Analysis results of the SMR–TES integration scenarios

The total amount of stored thermal energy can be validated using thermodynamic relations. The thermal energy stored in the TES system ($\boldsymbol{Q_{stored}}$) is calculated as a function of the sodium mass flow rate ($\boldsymbol{\dot{m}_{Na}}$), specific heat capacity ($\boldsymbol{C_{p,Na}}$), and the temperature difference across the IHX (($\boldsymbol{T_{out} - T_{in}}$)), as shown in Eq. (1):

$$\boldsymbol{Q_{stored}} = \boldsymbol{\dot{m}_{Na}} \cdot \boldsymbol{C_{p,Na}} \cdot (\boldsymbol{T_{out} - T_{in}}) \qquad (1)$$

Under the condition of a maximum steam extraction rate of 20% and a total sodium flow rate of 80 kg/s, the simulation results indicated a temperature difference of approximately 70 K Assuming an average specific heat capacity of liquid sodium of approximately 1.27 kJ/kg·K in this temperature range, the thermal power stored in the TES system is calculated at 7.1 MWth.

4. Conclusions

In this paper, an integrated model coupling an SMR with a TES system was developed using the MARS-KS code for system analysis. Through this model, the variation in thermal energy storage capacity of TES was evaluated as a function of the extracted steam flow rate at the steam generator outlet. In addition, the effect of liquid sodium flow rate on the stored thermal energy and temperature was analyzed. The results indicated that, under the maximum steam extraction flow rate of 20%, the TES system can store approximately 7.1 MWth of thermal power at the maximum sodium flow rate. Further analyses will be conducted for a wider range of operating conditions. These findings are expected to provide valuable input for future system design.

ACKNOWLEDGMENTS

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