Investigating Necessary Operating Conditions for TES Integrated to PWR SMRs to Maintain the Reactor Power

Takyun Chun [a], Gyudong Kim [a], Yong Jae Chae [a], Jeong Ik Lee [a*]
[a]*Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology (KAIST), 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea*

[*]*Corresponding author: jeongiklee@kaist.ac.kr*

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1. Introduction

According to the 2022 report from the International Energy Agency (IEA), the power sector is the largest source of annual CO_2 emissions [1]. The daily load curve demonstrates considerable fluctuations in electricity demand. Additionally, renewable energy sources such as solar PV and wind power are constrained by low capacity factors as shown in Table 1, which undermines their reliability for a stable power supply. Given these challenges, Small Modular Reactors (SMRs) have emerged as a promising solution for managing load variability. Their small-scale, modular design provides several advantages, including enhanced safety, increased site flexibility, and reduced construction risks. As shown in Table 1, SMRs also have higher capacity factors, which allow them to deliver more stable power than intermittent renewable sources.

The integration of Thermal Energy Storage (TES) with SMRs allows excess energy generated during low-demand periods to be stored and later released during peak demand. This integration enhances grid stability and supports the development of a more resilient and sustainable energy system [2].

When TES is integrated into a cycle, the added TES inlet and outlet flows interact with existing components, altering the overall system conditions. Therefore, the selection and design of TES materials must be optimized to match cycle conditions. Since the specifications of each component and the overall system are specified at the design point, operation must remain within these limits. Consequently, the integration of TES requires careful consideration of system constraints and the inlet/outlet conditions of the TES.

Under the same inlet conditions, the amount of stored energy and the outlet temperatures of steam or feedwater vary depending on the heat transfer performance and temperature of the TES. Therefore, once the TES design is determined, different control strategies should be applied based on its heat transfer performance and temperature. While PCM-based thermal storage devices maintain a relatively constant temperature range, sensible heat storage systems experience a temperature rise in the TES as heat is stored. As the TES temperature increases, heat transferred decreases, leading to a rise in the outlet temperature of the energy-transferring stream.

In this study, TES material selection and modeling were not conducted; instead, the analysis was performed under the assumption that a hypothetical TES was integrated into the system to investigate the impact of TES outlet conditions. The control strategies based on TES outlet temperature during the charging phase are analyzed, and their impact on the output of the SMR power cycle is investigated. The SMR layout used in this study is shown in Fig. 1, while the steady-state parameters and performance of the SMR power cycle without TES are summarized in Table 1I. The SMR power cycle output and control strategies based on TES outlet temperature are analyzed under quasi-steady-state conditions. These results are expected to contribute to future predictions of transient states and system design when integrating thermal energy storage systems with SMRs to enhance load-following capabilities.

Table 1: Capacity factors of power sources

Power source	Capacity factor	Installed capacity
Solar PV	0.13*	151.34 GW
Wind	0.20*	98.37 GW
SMR	0.86**	23.53 GW

* Average capacity factor from 2013 to 2022.
** Assume that the capacity factor of SMR is identical to that of commercial large-scale NPPs.

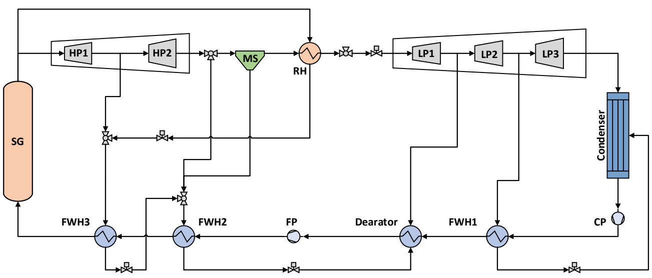

Fig. 1. Layout of SMR without TES

Table 1I. Cycle parameters/conditions for on-design

Cycle Conditions	Value
SG thermal power	546 MWth
SG outlet pressure	5.25 MPa
SG outlet temperature	297.8 ℃
SG inlet temperature	230.0 ℃
Condenser outlet temperature	40 ℃
Hot side pressure drop	3% of inlet
Cold side pressure drop	2% of inlet
Cycle Parameters	**Value**
Turbine efficiency	92%
Pump efficiency	85%
Generator efficiency	96%
Turbine pressure ratio	2.41 for HPT
	287.98 for LPT
Reheater bypass ratio	0.0785
HPT work	38.9 MW
LPT work	150.3 MW
Feedwater pump work	2.3 MW
Feedwater mass flow rate	284.6 kg/s
Net efficiency	32.87 %

2. Control Strategies

In this study, the case of steam extraction at the LPT inlet to TES for charging is analyzed as shown in Fig. 2. Assuming a constant heat input from the steam generator, a portion of the main steam flow is extracted to TES and then merged to the hot stream line of Feedwater Heater (FWH) 2nd stage. In this case, if the steam extraction flow rate after the HPT is not adjusted, the heat transfer to the 2nd stage of the FWH increases, causing the steam generator inlet temperature to continuously rise. To maintain a stable feedwater outlet temperature, the extraction flow rate at the HPT outlet must be reduced, which increases the reheater main steam flow rate. Therefore, system control is needed to increase the extraction fraction at the HPT outlet to the reheater in accordance with the increased main steam flow. When the hot stream flow to the reheater increases, the heat transfer to the feedwater in the 3rd stage of the FWH increases, resulting in a reduction of the extraction flow rate from the high-pressure turbine. While this behavior varies depending on the outlet temperature and the extraction fraction to TES, the general trend remains consistent with the mechanism described above.

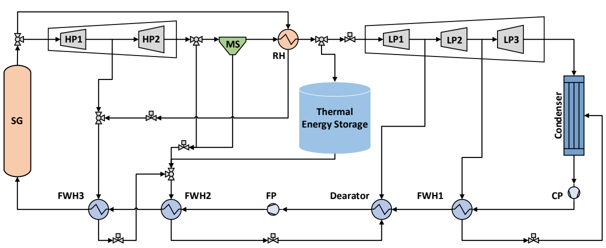

Fig. 2. Layout of SMR with TES for charge

3. Results and Discussions

SMR power cycle control is performed to maintain the same steam generator inlet conditions at the design point for extraction fractions to TES of 2%, 5%, 10%, and 15%. For the same TES inlet conditions, the TES outlet conditions are analyzed from superheated steam to a quality of x = 0.5. Under the pressure conditions considered in this study, phase transition from steam to water occurs when the steam temperature drops 75.97 °C below the inlet temperature, as shown in Fig. 3. The enthalpy values at the inlet, and outlet condition of quality x = 1.0 and x=0.5 of TES flow are 2996.5 kJ/kg, 2798.4 kJ/kg, and 1853.8 kJ/kg, respectively. This demonstrates that the enthalpy change during phase transition is significantly larger than that caused by sensible heat alone.

Fig. 4 shows the extraction fraction from the HPT outlet to TES for different TES extraction fraction. As the TES extraction fraction increases, the extraction fraction from the HPT outlet to the 2nd stage of the FWH decreases to maintain constant steam generator conditions. Under the same TES extraction fraction, if the TES fails to effectively store heat, resulting in a higher enthalpy of the TES outlet flow, the extraction fraction after the HPT decreases. Since the enthalpy of the fluid flowing through the TES changes significantly during the phase transition from steam to water, the extraction ratio from the HPT outlet varies greatly depending on the outlet quality x of the fluid flowing through the TES. When TES extraction reaches 15% and the outlet quality x is 1.0, the extraction fraction after the HPT is nearly eliminated. This implies that at an extraction fraction of 15%, if the fluid in TES does not transfer sufficient heat to the TES medium and retains high enthalpy, the system does not have converged operating state to meet all constraints. As shown in Fig. 4, for TES extraction fractions up to 10%, the system remains operable under the same steam generator conditions, as the extraction fraction after the HPT can be adjusted to compensate for a reduced inlet-outlet temperature difference of TES flow. However, when the TES extraction fraction reaches 15%, the extraction fraction after the HPT approaches zero when the TES inlet-outlet temperature difference is 60 °C. If this temperature difference decreases further, there is no state of the system that can satisfy to maintain the same steam generator conditions (i.e. the reactor power maintains 100% steady state). This indicates that when the extraction fraction is beyond 15%, insufficient heat removal by the TES prevents the outlet conditions from reaching saturation, and there is no state of the system that can meet all constraints imposed on the system.

As described in Section 2, an increase in TES extraction fraction redistributes flow within the power cycle: the extraction fraction after the HPT must decrease to avoid overheating the feedwater. This adjustment increases the flow from the HPT inlet to the reheater. However, because a part of the main steam is diverted to TES, the overall steam flow reaching the LPT decreases. This impacts the turbine output depending on how much heat is removed in the TES. The turbine output based on the temperature difference between the inlet and outlet of the fluid flowing through the TES and TES extraction fraction is presented in Fig. 5. The arrows in Fig. 5 indicate the range of quality from 1.0 to 0.5. Before phase transition from steam to water occurs, the turbine output decreases relatively slightly since the LPT inlet flow does not significantly vary. In the phase change region of the steam in TES, the enthalpy changes substantially, causing a significant reduction in the extraction fraction from the HPT outlet. This reduction leads to an increased extraction flow rate to the reheater from the HPT inlet, resulting in a decreased LPT inlet flow. Therefore, the substantial drop in enthalpy at the TES outlet significantly reduces the LPT inlet flow, which in turn leads to a notable decrease in LPT work. However, the decrease in LPT work is not directly proportional to the increase in TES extraction fraction, because the LPT inlet flow does not decrease correspondingly.

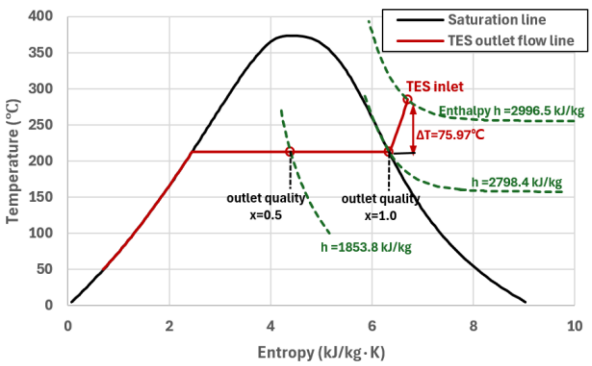

Fig. 3. TES outlet flow line in Temperature-Entropy (T-s) diagram

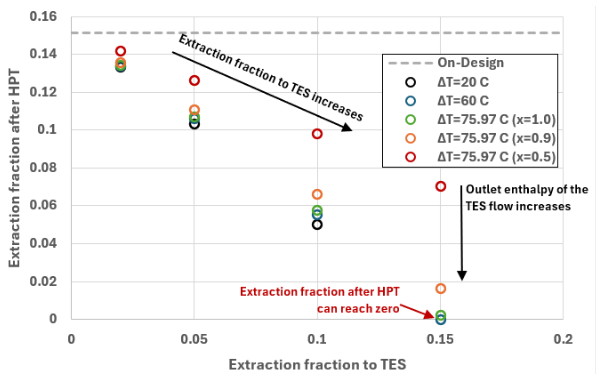

Fig. 4. Extraction fraction after HPT dependence of extraction fraction to TES

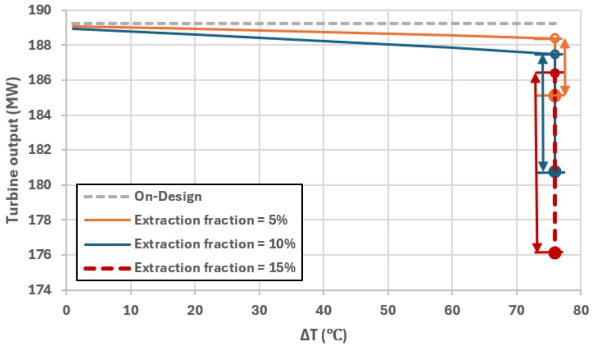

Fig. 5. Turbine output variation with different extraction fraction to TES and the inlet-outlet temperature difference $\Delta T = T_{in}$-T_{out} in TES

4. Summary and Conclusions

This study examines the integration of thermal energy storage (TES) with a Small Modular Reactors (SMRs) power cycle, focusing on impacts of TES outlet temperature during charging. Without TES material selection and modeling, the analysis assumes a hypothetical TES integrated into the system.

TES extraction fractions of 2%, 5%, 10%, and 15% are investigated, revealing that phase transition from steam to water significantly affects turbine performance due to substantial enthalpy variation of the fluid. Steam extraction at the low-pressure turbine (LPT) inlet for TES charging requires adjustments in the high-pressure turbine (HPT) extraction fractions to maintain stable steam generator conditions. Under the same TES extraction fraction, if the TES fails to effectively store heat from the TES flow, resulting in a higher enthalpy of the TES outlet flow, the extraction fraction after the HPT decreases. The state of the system does not exist for the SMR power cycle used in this study when the TES inlet-outlet temperature difference ($\Delta T = T_{in} - T_{out}$) becomes smaller than 60 °C at a TES extraction fraction of 15%. This indicates that as TES extraction increases, insufficient heat transfer performance of TES will eventually change the steam generator operating conditions, which in turn change the reactor power. This highlights the need for TES design with appropriate heat transfer performance when integrated to power cycle.

TES integration impacts LPT inlet flow and work output, particularly during phase transition from steam to water, with a nonlinear effect as TES extraction increases. Therefore, precise steam extraction control and careful TES management are crucial for effectively integrating TES with SMRs, enhancing system reliability and efficiency in load-following operations. Additionally, TES inlet and outlet flows interact with existing components, altering overall system conditions. To ensure stable operation, TES material selection and design must be optimized to align with cycle conditions while maintaining component functionality within design limits.

ACKNOWLEDGEMENTS

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