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Preliminary Study on the effects of Steam Extraction on the BOP Systems in i-SMR

Hyeon-Min Seo [a*], Jungjin Bang[a], Jehee Lee[a], Bub Dong Chung
[a]*FNC Tech. Co. Ltd., Floor 32, Heungdeok IT Valley, 13 Heungdeok 1-ro, Giheung-gu, Yongin-si, Gyeonggi-do, 16954, Republic of Korea*
** Email: alsdkdzh1@fnctech.com*

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1. Introduction

Currently, Small Modular Reactors (SMRs) are being actively developed worldwide, including the i-SMR in South Korea, which is in its development phase. One of the key requirements of i-SMR is its capability for multipurpose utilization. This involves using the thermal energy generated by the steam generator not only for electricity production but also for industrial applications such as hydrogen production, seawater desalination, and district heating.

However, steam extraction can introduce sudden transients that impact the Balance of Plant (BOP) system. Additionally, supplying thermal energy of nuclear power plant to the industry process heat can reduce the feedwater temperature. Furthermore, during multipurpose utilization, variations in turbine output due to changes in steam extraction flow must also be considered. Therefore, a model of the BOP is essential for analyzing such transient conditions.

In this study, the BOP of i-SMR, including turbines and extraction lines, was modeled using the MARS-KS code [1]. A preliminary analysis of steam extraction operation was performed to evaluate key parameters in the BOP, such as turbine performance and feedwater temperature behavior. The results of this study can provide insights into transient behavior in the BOP system during multipurpose utilization and load-following operations. Additionally, the findings can serve as fundamental data for establishing operational strategies.

2. MARS-KS Modeling for BOP of i-SMR

2.1 BOP modeling description and modeling setup

Fig. 1 shows a schematic diagram of the BOP system during the basic design phase of i-SMR. The BOP includes various components such as the Helical Steam Generator (SG), High-Pressure Turbine (HP-Turbine), Low-Pressure Turbine (LP-Turbine), Condenser, Condensate and Feedwater Pumps, Deaerator, Low- and High-Pressure Feedwater Heaters (LPFH/HPFH), Moisture Separators, and Reheaters (MSR).

Fig. 2 illustrates the BOP modeling of i-SMR using MARS-KS1.5. All major components, including the steam generator (SG), were modeled. The inlet and outlet conditions of the SG on the primary side were modeled as boundary conditions. A foundation for the component modeling in this work was provided by the development of BOP input models in a previous study [2].

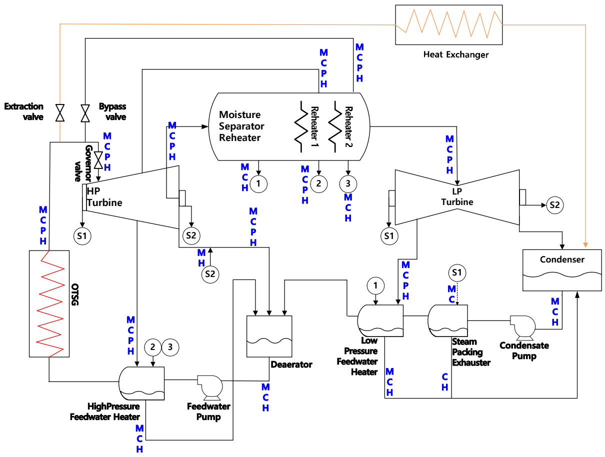


Fig. 1. Schematics of BOP for i-SMR (Basic design)

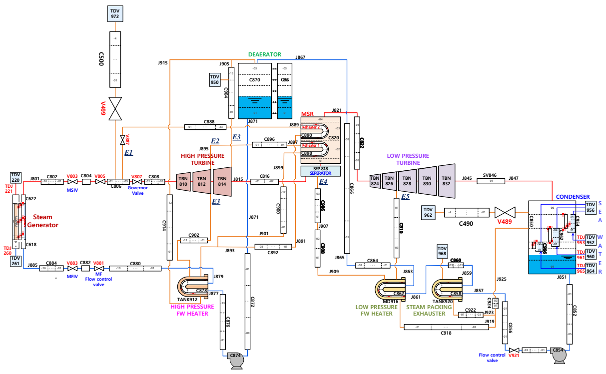
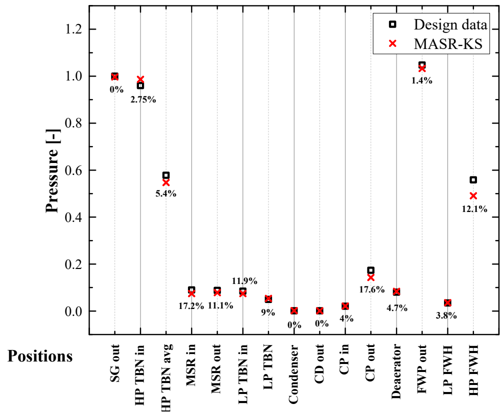


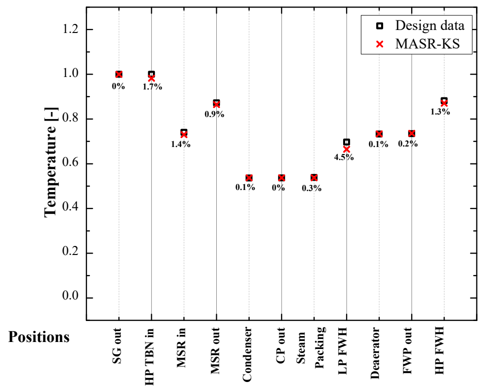
Fig. 2. MARS-KS Nodalization for i-SMR

2.2 Verification of BOP modeling

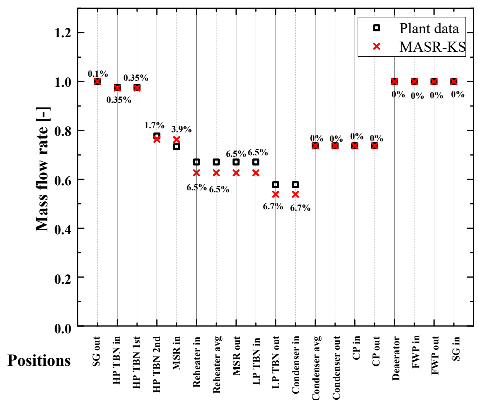
To ensure the reliability of the developed input model, we compared the MARS-KS results with i-SMR basic design data. Fig. 3 presents the benchmarking results for major components of the BOP system in terms of pressure (a), temperature (b), and flow rate (c). Overall, the thermal-hydraulic behavior of all components was reasonably well predicted, with an average error of 2.3%. The modeling will be continuously improved to reduce some discrepancies.



(a) Pressure



(b) Temperature



(B) Mass Flow Rate

Fig. 3. Steady State of i-SMR using MARS-KS

3. Analysis results of Steam Extraction Condition

In this section, a preliminary analysis of steam extraction was performed using the developed model. The steam extraction point was selected at the steam generator outlet pipe, where the steam temperature is the highest. The steam extraction rate was controlled by adjusting the valve area (V499), as shown in Figure 2. In addition, it was assumed that 100% of the extracted steam condenses and is directed into the condenser.

Unfortunately, the current BOP modeling does not include the primary system, making it incapable of simulating the impact of core temperature variations caused by changes in feedwater temperature. To address this limitation, a primary system model will be developed in future work and integrated with the currently developed input model. Table 1 presents the steam extraction scenarios, where the extraction rate was assumed to increase stepwise from a minimum of 5% to 25%.

Table I: Steam extraction scenarios

Time [sec]	Extraction rate [%]
0-100	0
100-600	0-5
600-1000	5
1000-2000	5-10
2000-3000	10
3000-4000	10-15
4000-5000	15
5000-6000	15-20
6000-7000	20
7000-8000	20-25
8000-10000	25

Fig. 4 presents the steam flow rate in the extraction pipe. The red line represents the steam extraction scenario, while the dashed line indicates the MARS-KS simulation results. As steam extraction increases up to 25%, a slight delay is observed. However, the flow rate of the extracted steam is generally well-controlled.

Fig. 5 shows the impact of steam extraction on SG temperatures, showing a reduction in steam temperature by approximately 2.3% and a decrease in feedwater temperature by about 7.4%. This temperature drop occurs because a portion of the steam, originally allocated for heat transfer in the feedwater heat exchanger, is diverted for multipurpose use, resulting in insufficient heat transfer to the feedwater. Given that feedwater temperature variations can influence the design of the primary system and core reactivity, it is necessary to derive an operational strategy that minimizes feedwater temperature variance to ensure stable steam extraction operation.

Fig. 6 compares the steam extraction rate and turbine output. The x-axis represents the fraction of steam extracted during steam extraction operation, while the y-axis indicates the reduction in turbine output. In other words, if the x-axis and y-axis have the same value, it means that the turbine output decreases in proportion to the extracted steam fraction. The calculation results show that up to approximately 8% of the extraction flow rate, the reduction in turbine output follows an almost 1:1 ratio with the extracted steam fraction. However, beyond this point, the rate of turbine output reduction becomes larger than the steam extraction fraction. This phenomenon occurs because the turbine output is a function of both mass flow rate and enthalpy. That is, not only does the mass flow rate of steam entering the turbine decrease, but the temperature of the main steam also decreases, leading to a compounded effect that results in a greater reduction in turbine output.

Fig. 7 shows that as the steam extraction amount increases, the turbine power should decrease proportionally. However, due to steam extraction, the inlet flow rate to the turbine decreases, and the enthalpy at the steam generator inlet also decreases, resulting in a slightly greater reduction in output compared to the extracted flow rate.

Fig. 8 shows that the pressure is maintained by the Governor valve control logic, which effectively stabilizes the steam generator pressure.

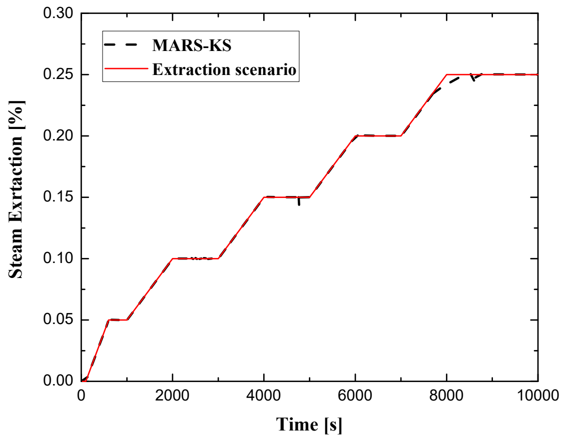


Fig. 4. Steam extraction scenario

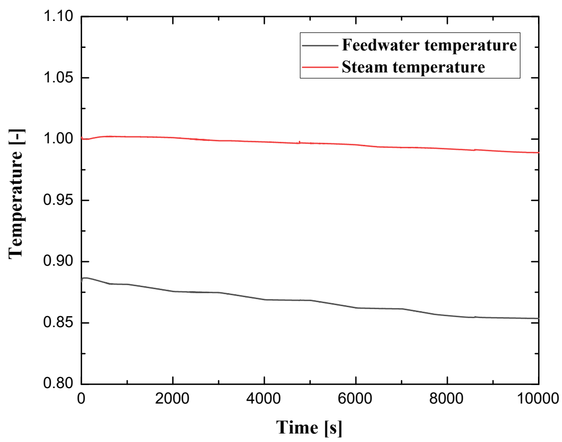


Fig. 5. Feedwater/Steam Temperature

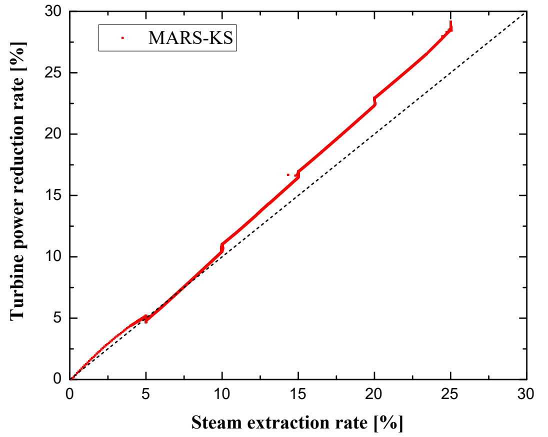


Fig. 6. Turbine and Extraction ratio

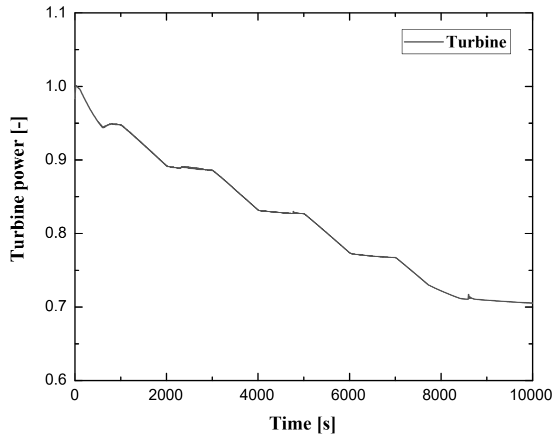


Fig. 7. Turbine Power

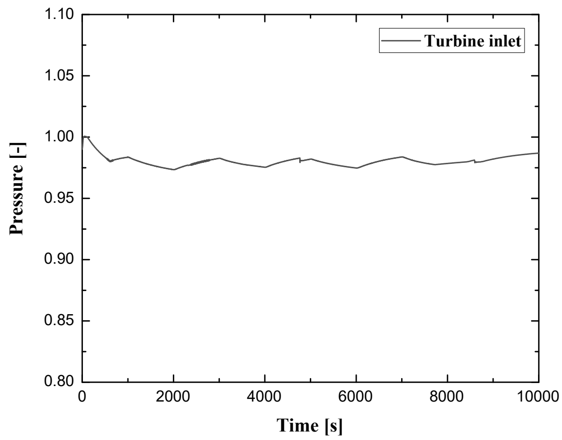


Fig. 8. Turbine inlet Pressure

4. Conclusions

In this study, we developed the BOP modeling of i-SMR using MARS-KS 1.5, and its accuracy was verified by comparing the results with i-SMR basic design data. Based on this validated model, steam extraction operation was calculated. It was confirmed that as the steam extraction rate increased, the turbine output decreased at a rate slightly greater than a 1:1 ratio. This phenomenon is attributed to both the reduction in mass flow entering the turbine and the decrease in enthalpy at the steam generator outlet due to steam extraction. Additionally, it was observed that steam extraction led to a decrease in feedwater temperature by approximately 7.4%, which can directly influence the thermal-hydraulic behavior of the primary system and core reactivity.

Since the primary system was treated as a boundary condition in the current model, its impact on core inlet and outlet temperatures could not be assessed. To overcome this limitation, future research will focus on developing an integrated model that couples the primary and BOP systems. It will enable a more comprehensive evaluation of transient behavior and operational strategies for multipurpose utilization and load-following operation in i-SMR.

ACKNOWLEDGMENTS

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