Preliminary Investigation on the Primary Side Temperature Control with Secondary Side Thermal Hydraulic Control in PWR based SMR.

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1. Introduction

As the global demand for clean and sustainable energy continues to grow, Small Modular Reactors (SMRs) have emerged as a promising solution for nuclear power generation. SMRs are particularly advantageous due to their compact design, modular construction, and enhanced safety features. These reactors offer flexibility in site selection, reduced capital investment, and shorter construction periods, while also minimizing the operational costs and staffing requirements associated with traditional large-scale reactors [1].

One of the key challenges in SMR design and operation lies in the development of efficient and simplified control systems. Traditional chemical reactivity control methods, such as the use of soluble boron for pressurized water reactor (PWR), add complexity and increase maintenance burdens. In response, considerable research is focused on reducing or eliminating these chemical control systems by leveraging the inherent safety features of PWR type SMRs, such as the negative Moderator Temperature Coefficient (MTC) [2]. The negative MTC allows for passive regulation of reactor power, where an increase in core temperature leads to a reduction in reactivity, enhancing reactor safety and simplifying the overall control framework.

This study explores a novel approach to power regulation by focusing on the secondary side of the reactor, specifically the steam generator, to investigate how variations in the Number of Transfer Units (NTU) affect the primary-side temperature. The NTU, which quantifies the heat transfer efficiency in a heat exchanger, plays a critical role in determining the overall performance of the heat exchange process. In this research, the authors examine how changes in NTU, while maintaining constant inlet and outlet conditions on the secondary side, impact the primary-side temperature and, consequently, the reactor power output.

By adjusting the NTU of the steam generator, the heat transfer efficiency is hypothesized that it can influence the primary-side temperature, thereby passively modulating reactor power through the negative MTC. This study aims to systematically investigate this relationship across a range of power output levels, from 25% to 100%, using the KAIST-QCD model (Quasi-steady state cycle optimization model of the secondary cycle developed in MATLAB). The primary objective is to demonstrate that by controlling NTU on the secondary side, significant variations in the primary-side temperature can be achieved, leading to passive regulation of reactor power without relying on complex chemical control systems or mechanical control measures.

The findings of this research are expected to contribute to the ongoing development of SMRs, providing insights into how secondary-side adjustments, such as NTU control, can be used to regulate primary-side temperatures and reactor power more effectively. This approach offers a pathway toward simplifying reactor control systems and reducing operational complexity.

2. Methods

2.1 Rankine Cycle

In this study, quasi-steady state simulations were carried out under partial load conditions for a power cycle designed for a Small Modular Reactor (SMR). This cycle was initially developed in previous research [3]. The cycle configuration includes a moisture separator, reheater, deaerator, and three feedwater heaters (refer to Fig. 1). Table I presents the on-design cycle parameters and performance metrics, which were established in prior studies. Based on these design values, performance assessments were made for thermal power output levels of 100%, 75%, 50%, and 25%. Notably, the net efficiency of the cycle decreased from 33.54% at full thermal power to 19.02% at 25% output, while the steam generator (SG) inlet temperature dropped from 229.9°C at full power to 162.7°C at 25% power (Table II). Detailed thermodynamic properties at specific cycle points are available in the output-specific T–s diagrams shown in Fig. 2.

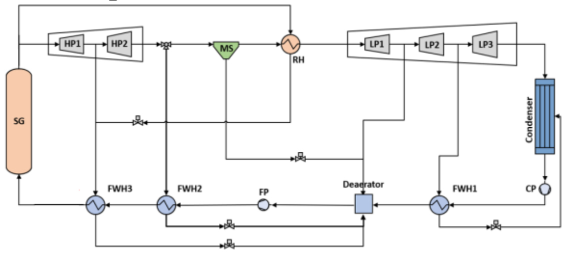

Fig. 1. SMR preliminary analysis cycle layout.

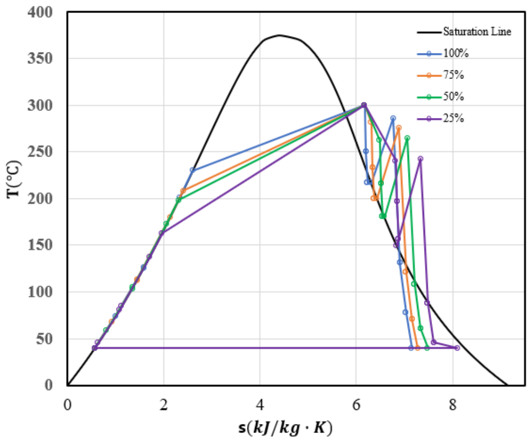

Fig. 2. T-s diagram of Rankine cycle by thermal power percentage.

Table I: Cycle parameters

Parameters	Value
SG thermal power	500MWth
SG outlet temperature	300°C
SG inlet pressure	5.335MPa
SG outlet pressure	5.25MPa
Reheater bypass	7.85%
HPT pressure ratio	1.55
LPT pressure ratio	6.45
Condenser T & P	40°C (7.38kPa)
Turbine isentropic efficiency	85%
Pump efficiency	80%
Hot side pressure drop	9%
Cold side pressure drop	7%
Net efficiency	33.54%

Table II: Cycle performance by thermal power percentage.

SG Load (%) / Cycle Parameters	25	50	75	100
SG FW inlet mass flow rate (kg/s)	55.70	120.44	184.68	259.64
SG FW inlet temperature (°C)	162.7	192.5	206.4	229.9
Cycle Performance	**Value**			
HPT work (MW)	7.98	16.89	25.85	35.73
LPT work (MW)	16.95	55.70	93.61	134.05
Pump work (MW)	1.15	1.35	1.62	2.1
Cycle Q_{in} (MW)	125	250	375	500
Net efficiency (%)	19.02	28.49	31.42	33.54

2.2 Steam Generator

To evaluate the influence of the steam generator's NTU characteristics on the primary side, the steam generator was modeled as a counter-flow heat exchanger. The reference operating condition was set such that the steam generator maintains an NTU of 2.0 to 3.5 at 100% thermal power. Additionally, considering the primary side pressure of 13.8 MPa (as used by NuScale), the steam generator inlet temperature was constrained to not exceed 320°C at full power, with a boiling point of 335°C. The steam generator model is illustrated in Fig. 3. It should be noted that this preliminary study does not account for pressure drop in the SG, which will be included in subsequent phases of the research.

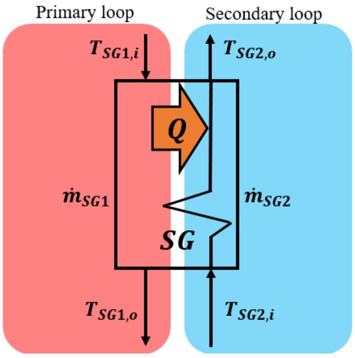

Fig. 3. Schematic diagram of Steam Generator.

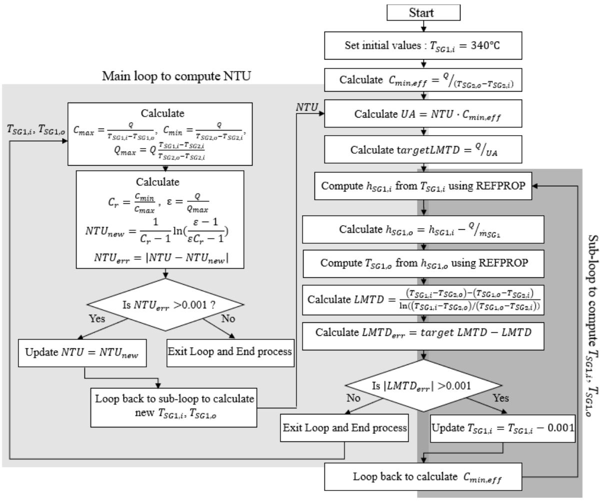

Fig. 4. Flow chart of the procedure for computing the primary side temperature under varying secondary side conditions and varying NTU characteristics [4].

The heat transferred from the primary side to the secondary side, denoted as Q, is expressed as:

$$Q = UA \cdot LMTD = \dot{m}_{SG1}\left(h_{SG1,i} - h_{SG1,o}\right). \ (1)$$

where UA is the overall heat transfer coefficient, defined as:

$$UA = NTU \cdot C_{min,eff}. \ (2)$$

Here, $C_{min,eff}$ represents the effective minimum heat capacity of the secondary side, calculated as:

$$C_{min,eff} = \frac{Q}{T_{SG2,o} - T_{SG2,i}}. \ (3)$$

Since the specific heat capacity (C_p) changes significantly during phase change, the effective heat capacity is used. Consequently, the heat transfer Q is given by:

$$Q = NTU \cdot \frac{Q}{T_{SG2,o} - T_{SG2,i}} \cdot \frac{(T_{SG1,i} - T_{SG2,o}) - (T_{SG1,o} - T_{SG2,i})}{\ln\left(\frac{(T_{SG1,i} - T_{SG2,o})}{(T_{SG1,o} - T_{SG2,i})}\right)}. \ (4)$$

With the known secondary side inlet and outlet temperatures, and the primary side inlet temperature, the primary side outlet temperature $T_{SG1,o}$ can be determined. Furthermore, using the enthalpy difference between the primary side inlet and outlet at 13.8 MPa, the primary side mass flow rate is calculated as:

$$\dot{m}_{SG1} = \frac{Q}{h_{SG1,i} - h_{SG1,o}} \quad . (5)$$

The procedure for determining the primary side temperature under varying NTU is detailed in the flowchart shown in Fig. 4 (sub-loop). As the thermal power decreases, the secondary side mass flow rate also reduces, which necessitates accounting for the increasing NTU values corresponding to the reduced flow rate. The flowchart of main loop in Fig. 4 illustrates the process of incorporating the reduced flow rate into the NTU calculation.

3. Results

Fig. 5 illustrates the primary side temperature and NTU values for various thermal power when the NTU at 100% power is assumed to be 2.0, 2.5, 3.0, and 3.5. NTU determines the heat transfer per unit mass, which serves as an indicator of the heat transfer efficiency. It has a significant impact on both the performance of the heat exchanger and the temperature variation. A higher NTU indicates an increase in heat transfer area or overall heat transfer coefficient, or a reduction in flow rate, leading to an improvement in heat transfer efficiency. At higher NTU values, the NTU values at lower power increased significantly, and the average primary side temperature also showed a larger increase compared to the 100% power condition. In Fig. 6(a), the change in the average primary side temperature for 25% to 100% thermal power is shown for various NTU value. When the NTU was set to 3.5, a temperature increase of over 6°C was observed. As the NTU decreased, the temperature increase became smaller, and at NTU 2.0, the temperature tended to decrease. Figure 6(b) shows the temperature change on the primary side when the mass flow rate was linearly decreased from 25% to 100% of the full load (at 25% load, an additional 10% flow rate is applied, while at 100% load, the flow rate remains the same as the baseline). The results indicate that as NTU increases, the temperature changes due to mass flow rate variations becomes more pronounced. Table III presents the primary side mass flow rate changes $\Delta\dot{m}_{SG1}$ and the ratio of mass flow rate changes to temperature changes $\frac{\Delta\dot{m}_{SG1}}{\Delta T_{SG1,avg}}$ as thermal power increases, assuming a linear decrease in the primary side flow (same mass flow rate program with Fig. 6(b)) for various NTU. The ratio of mass flow rate changes to temperature changes $\frac{\Delta\dot{m}_{SG1}}{\Delta T_{SG1,avg}}$ representing the burden of mass flow changes for increasing the primary side temperature. The burden for increasing the average primary side temperature at NTU 2.0 is 4 to 5 times higher than that at NTU 3.0.

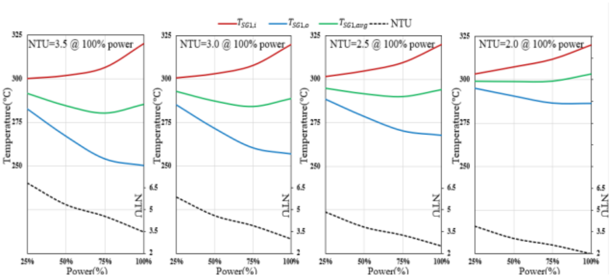

Fig. 5. Primary side inlet, average and outlet temperature (red, green and blue line) and NTU values (black dotted line) for various thermal power percentages when the NTU at 100% thermal power is assumed to be 3.5, 3.0, 2.5 and 2.0.

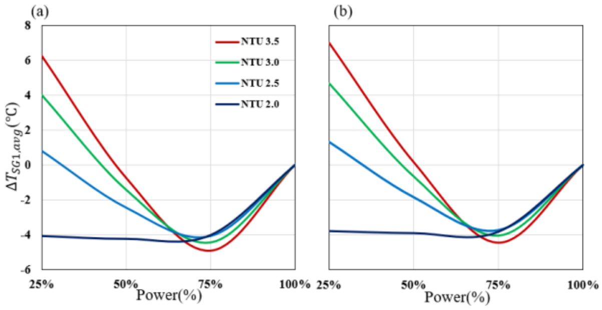

Fig. 6. (a)The change in the average primary side temperature for 25% to 100% thermal power for various NTU value. (b) The temperature change on the primary side when the mass flow rate was linearly decreased from 25% to 100%.

Table III: $\Delta\dot{m}_{SG1}$ and $\frac{\Delta\dot{m}_{SG1}}{\Delta T_{SG1,avg}}$ as thermal power increases, assuming a linear decrease in the primary side flow for various NTU.

Power(%) / NTU	25%		50%		75%		100%	
	$\Delta\dot{m}_{SG1}$	$\frac{\Delta\dot{m}_{SG1}}{\Delta T_{SG1,avg}}$	$\Delta\dot{m}_{SG1}$	$\frac{\Delta\dot{m}_{SG1}}{\Delta T_{SG1,avg}}$	$\Delta\dot{m}_{SG1}$	$\frac{\Delta\dot{m}_{SG1}}{\Delta T_{SG1,avg}}$	$\Delta\dot{m}_{SG1}$	$\frac{\Delta\dot{m}_{SG1}}{\Delta T_{SG1,avg}}$
3.5	169.94	220.19	113.29	121.67	56.65	116.08	0.0	0.0
3.0	188.11	278.01	125.41	159.29	62.70	149.39	0.0	0.0
2.5	226.94	418.74	151.29	245.32	75.65	217.84	0.0	0.0
2.0	347.81	1058.51	231.87	621.32	115.94	507.30	0.0	0.0

4. Summary and Conclusions

This study demonstrates the significant impact of NTU characteristics on the primary side temperature regulation in Small Modular Reactors (SMRs). The results suggest that for the same primary side mass flow rate, higher NTU values can effectively increase the average primary side temperature under low load conditions. This offers a promising pathway for reducing the reliance on control rods, particularly in SMRs that exhibit a strong negative Moderator Temperature

Coefficient (MTC), thereby enhancing operational safety and efficiency.

The findings also show that, when aiming to increase the primary side temperature during low-load conditions, higher NTU values lead to greater temperature increases with a smaller increase in primary side mass flow rate. This implies that careful tuning of NTU values can provide more effective thermal management, allowing for more efficient use of the available mass flow rate and minimizing the associated operational costs.

However, while increasing the NTU offers advantages in temperature control, this approach does come with challenges. Higher NTU values require a larger heat transfer surface area and a greater overall heat transfer coefficient, which impose spatial and economic constraints. As such, optimizing the NTU involves balancing the benefits of higher heat transfer efficiency with the need for larger, more expensive equipment.

The study also emphasizes the importance of finding an appropriate balance between the available mass flow rate variation on the primary side and the NTU value. This balance is crucial for maintaining both efficient thermal management and practical design constraints in SMR systems. Future work will need to explore how these parameters can be optimized in real-world applications, taking into account the full range of operational conditions and potential trade-offs.

In summary, increasing NTU values in the steam generator offers a promising strategy for improving the primary side temperature control and reducing the need for active control measures. However, the challenges associated with space, cost, and system design must be carefully addressed to ensure the overall viability of this approach in SMR development.

Acknowledgements

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