Coupling Analysis of SMART100 for Thermal Energy Extraction

Keon Yeop Kim [a*], Youngsuk Bang [a], So Eun Shin [a], Jung Jin Bang [a]
[a]*Future and Challenge Tech. Co. Ltd., Heungdeok 1ro 13, Yeongdeok-dong, Giheung-gu, Yongin-si, Gyeonggi-do*
[*]*Corresponding author: kykim@fnctech.com*

1. Introduction

Nuclear-Renewable Hybrid Energy System (NRHES) is a conceptual system that integrates the nuclear, renewables, energy storage and industry customers to maximize economical competiveness and operational stability [1]. For example, the intermittency of renewable energy sources can be compensated by adjusting steam flows to turbines in nuclear power plants and utilizing thermal energy for industrial applications (e.g., hydrogen production, desalination, district heating, thermal energy storage). The small modular reactor (SMR) is well-suited as a component of NRHES in that it can be installed near the locations where electricity or thermal energy would be required.

The most viable way of utilizing thermal energy of SMR could be a steam extraction. Due to safety and operation issues (e.g., accident management, reactivity feedback), the primary side would not be appropriate. With a proper design, the heat can be extracted from the secondary side without perturbing the primary side while maintaining the reactor full power.

In this study, the impact analysis of SMR due to steam extraction and return from the secondary side of SMR has been performed. Firstly, SMART100 has been modelled by using a Modelica language. The sub-systems (i.e., reactor core, once through steam generator (OTSG), secondary side) have been modelled and integrated. Secondly, the analyses with different points of steam extraction and return have been conducted and the pros/cons are compared.

2. SMART100 Modeling

The sub-systems which is reactor core, OTSG, secondary system) of SMART100 are modeled using a Modelica language. Each sub-system model is validated using design data and analysis results by system analysis code.

2.1 Core model

Point kinetics equation [2] with six-groups of delayed neutron precursor is applied to the core power calculation. Mann's model [3] is adopted for modeling thermal-hydraulic behaviors of the reactor. The coolant system is modelled as two lumped nodes and the fuel as one node. Dittus-Boelter correlation is applied to heat transfer between nuclear fuel and coolant. The schematic of the core model is presented in Fig.1.

The results under 100% power operation condition of the SMART100 are compared, The absolute errors of the core outlet temperature before mixing with core bypass flow and the core outlet temperature after mixing with core bypass flow are 0.0185 and 0.0051 %, respectively.

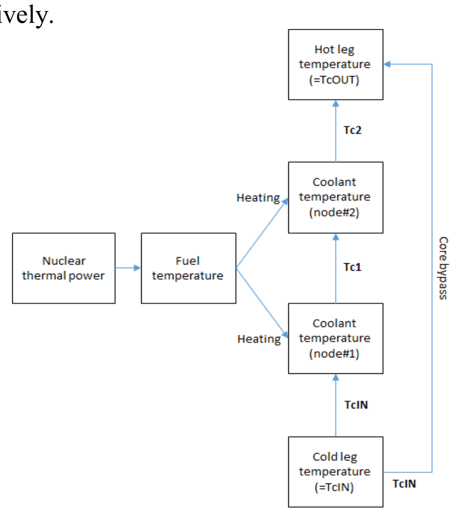

Fig.1. Schematic of SMART100 Core Model

2.2 OTSG Model

Helically coiled OTSG of SMART100 is modelled by a moving boundary approach. The locations of interfaces of subcooled region – boiling region and boiling region – superheated region are set to variable and the interfaces of heat transfer regions are determined as the saturated conditions of liquid and vapor. Therefore, the location of the interfaces would be explicitly calculated as unknowns.

The various heat transfer and pressure drop correlations are implemented for comparisons. Fig.2 presents the comparison results of the OTSG Module with respect to MARS-KS simulation results.

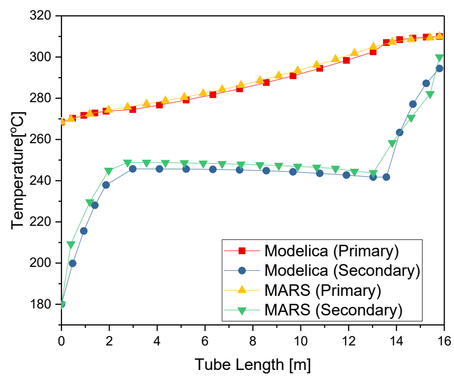

Fig.2. OTSG Calculated Temperature Profile

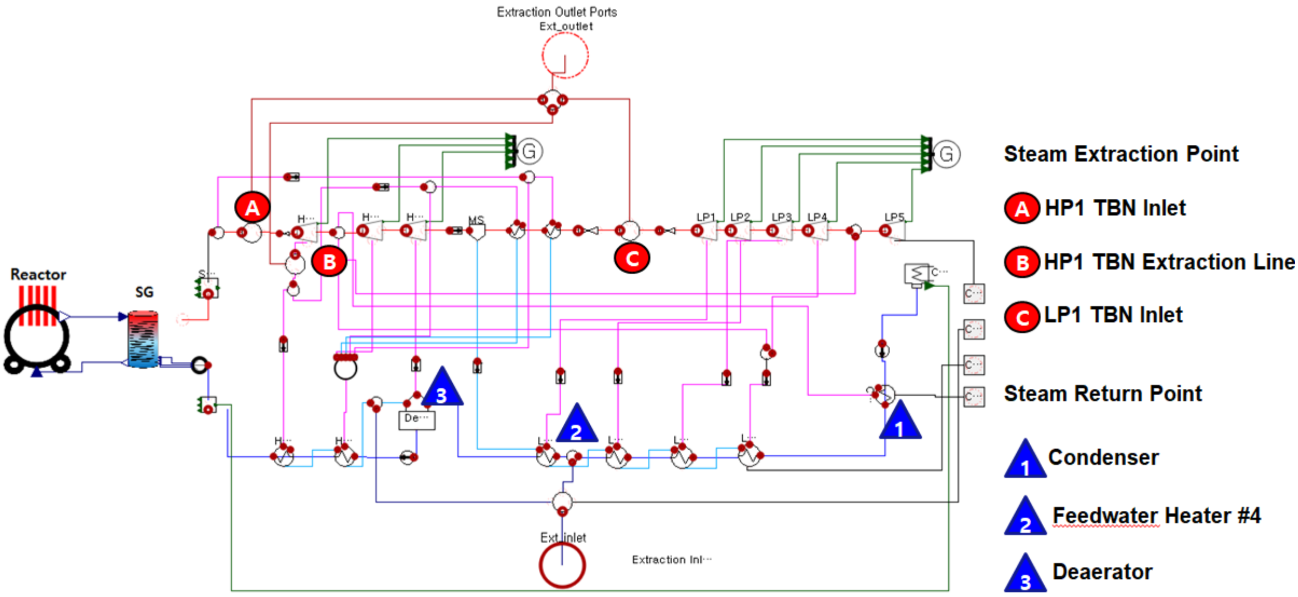

Fig.3. The Schematic of the SMART100 Integrated Modelica Model.

2.3 Secondary Side Model

Secondary side consists of the multi-stages of the high pressure turbine and low pressure turbines and condenser, and multi stage feedwater heaters and deaerator. Turbine stage is modeled as a simple turbine applying Stodola's Law [4] for modeling multistage turbines.

The Modelica results and secondary heat balance diagram [5] of the MGR (maximum guaranted rating) and VWO (valve wide open) are compared for turbine model validation. Almost all errors are within 5% and the secondary system model is available. The validation results of the secondary system are presented in Table 1.

Table.1. Validation Results of Secondary System Model

Location (Outlet)	Absolute Error (MGR)			Absolute Error (VWO)		
	Mass Flow Rate (%)	Pressure (%)	Enthalpy (%)	Mass Flow Rate (%)	Pressure (%)	Enthalpy (%)
HP1	0.002	0.450	0.651	0.001	5.019	1.113
HP2	0.003	6.514	2.379	0.004	1.784	2.676
HP3	0.002	0.000	0.631	0.005	4.212	0.882
LP1	0.834	0.000	0.050	1.033	0.385	0.283
LP2	0.833	0.000	0.050	1.004	4.181	0.196
LP3	0.833	0.000	0.056	0.965	4.363	0.315
LP4	0.834	0.000	0.607	0.806	4.231	0.916
LP5	0.832	0.000	0.265	0.811	0.000	0.184

2.4 Integrated Model

The SMART100 integrated Modelica model is developed by coupling with sub-system such as core, OTSG, and secondary side. The core inlet & outlet are connected to the outlet & inlet of the primary side of the steam generator, and the secondary steam generator outlet enthalpy is delivered to the inlet of the secondary side. Fig.3 presents the schematic of the SMART 100 integrated model.

3. Modelica Analysis

3.1 Analysis condition

Modelica analysis is conducted on the three steam extraction and three return points when the extracting steam is used in SMART100 normal power operation. The steam extraction & return points are presented in Fig.3. It is assumed that the extracted steam is used as a process heat and the returned in a state of 0.3 MPa, 1200 KJ/Kg (saturated water saturated steam mixture). And 5 percent of steam extraction is assumed.

The flow rate of the main steam and extraction steam of HP tubine1 on the normal operation is 186.3 kg/s, 32.86 kg/s, respectively.

3.2 Analysis Results

The analysis results of the extracted steam temperature, feedwater enthalpy and HP & LP turbine power are analyzed according to steam extraction & return points. The results are presented in Table.2.

Table.2. The Modelica Analysis Results

Steam Extraction Location	Return Location	Flow Rate [kg/s]	Extraction Steam Temp. [C]	Feedwater Enthalpy [KJ/kg]	HP Turbine Output [MW]	LP Turbine Output [MW]
HP TBN1 Inlet	Condenser	9.32	293.32	616.77	54.38	58.64
	Feedwater Heater #4 Inlet	9.32	293.32	651.42	54.38	58.64
	Deaerator	9.32	293.32	651.40	54.38	58.64
HP TBN1 Steam Extraction Line	Condenser	1.64	246.00	615.24	58.58	62.60
	Feedwater Heater #4 Inlet	1.64	246.00	621.71	58.58	62.60
	Deaerator	1.64	246.00	621.71	58.58	62.60
LP TBN1 Inlet	Condenser	6.16	235.21	616.71	58.58	59.54
	Feedwater Heater #4 Inlet	6.16	235.21	640.16	58.58	59.54
	Deaerator	6.16	235.21	640.15	58.58	59.54

As a result of analysis, if the steam is extracted from inlet HP turbine1, highest temperature steam can be obtained. The higher the steam temperature, the extraction steam is more usable as a heat source. However the turbine power and the core stability are deteriorated. If the steam is extracted from HP turbine1 extraction line, low temperature and low flow rate steam can be obtained, however the turbine power and the core stability are less affected. In case of extraction from the LP1 turbine, intermediate temperature, flow rate and turbine power can be obtained.

If the steam is returned to the condenser, secondary side stability is little affected. Enthalpy of the feedwater pump inlet does not increasing, cavitation of the feedwater pump would not be caused. In case of the steam is returned to the feedwater #4 heater and the deaerator, inlet enthalpy of the feedwater pump is increasing and cavitation can be caused. Evaluation results of the steam extraction & return location are summarized in Table.3. O means advantage, Δ means normal and X means weakness for these locations.

Table.3. Evaluation Results of the Steam Extraction/Return Points

Extraction /Return	Location	Steam Temp.	Steam Flow-rate	TBN Power	Core Stability	FW Pump Stability
Extraction	HP TBN 1 Inlet	O	O	X	X	-
	HP TBN 1	X	X	O	O	-
	LP TBN 1 Inlet	Δ	O	Δ	O	-
Return	Condenser	-	-	Δ	-	O
	Feedwater Heater #4 Inlet	-	-	O	-	X
	Deaerator	-	-	O	-	X

4. Conclusions

Component models of SMART100 has been developed by using a Modelica language and integrated for systematic analyses of steam extraction and return. It has been identified that there are pros and cons depending on the selection of a steam extraction point and a return point. The developed models will be utilized to configure an economically optimized NRHES and to develop an efficient control logic.

REFERENCES

[1] Y. Bang et al, A Study on Flexibility Modeling of Nuclear-Renewable Hybrid Energy System, Transactions of the Korean Nuclear Society Autumn Meeting Goyang, Korea, October 24-25, 2019.

[2] John R. Lamarsh, Introduction to Nuclear Engineering Third Edition, 2013.

[3] T.W. Kerlin. Dynamic Analysis and Control of Pressurized Water Reactors. Academic Press, Volume 14, Ney York, 1978.

[4] Stodola, A., Steam and Gas Turbines Volume 1. New York Peter Smith, 1945

[5] KHNP, KAERI, KACARE, SMART100 Standard Safety Analysis Report, 2019.