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Investigation of Computational Dynamic Modeling of Helical Once-Through Steam Generator for Integrated System Analysis

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1. Introduction

Nuclear-Renewable Hybrid Energy System (NRHES) is a conceptual system that integrates the nuclear, fossil, renewables, energy storage and industry customers to maximize economical competiveness and operational stability. Depending on the electricity demand and renewable energy generation, a portion of thermal energy utilization for electricity generation can be varied while the reactor operated constantly in the full power. The thermal energy of NPP can be extracted in a form of steam from the steam line and delivered to the process heat application facility.

By the way, the Small modular reactor (SMR) has various advantages in Nuclear-Renewable Hybrid Energy System (NRHES) thanks to its relative small power production, small-scale components and modular construction. It could be constructed near an application plant independently or as a group depending on market demand. Therefore, it could minimize the loss in transmission of energy (e.g., electricity, heat), enhance the financial investment affordability, and improve the energy utilization efficiency and economic revenue. To achieve the successful incorporation in NRHES, SMR should have the flexible operation capability, e.g., dynamic continuous power maneuvering or switching between applications.

SMART has helically coiled Once-Through type Steam Generators (OTSGs) [1]. The performance of the turbine would be determined by the enthalpy difference between inlet and outlet. As the higher the inlet enthalpy would be, the higher the turbine performance would be expected. Therefore, the inlet condition of steam, which is the outlet condition of OTSG would be the one of key parameters of the turbine cycle performance. If the heat is extracted from the turbine cycle, the feedwater inlet condition would be perturbed and the heat balance would be changed. This change would be propagated to the primary side and ultimately, the reactor core reactivity would be varied, which requires the reactivity controls and operation/safety concerns. Therefore, dynamic analysis of nuclear power plant model should be performed.

In this study, the 3-node dynamic model of OTSG is developed by improving the previously developed steady-state model. OTSG steady-state model can be utilized in designs, but transient simulations are limited. OTSG dynamic model coupled with core and secondary model can be used to examine plant behavior under transient conditions such as steam extraction to use plant heat. The mathematical formulation has been derived by using the moving boundary approach and implemented by using Modelica environment [2].

2. Development of OTSG Modelica Dynamic Model

The OTSG dynamic model has been developed using Modelica. Fig.1 presents the schematic of the OTSG. The primary coolant flows from the top to the bottom of the shell side and transfers heat to the secondary side. The secondary water supply flows from the bottom of the tube side, and the superheated steam is discharged from the top of the steam generator. The moving boundary is determined according to the quality of the secondary feedwater in S/G, and the heat transfer region is divided. The three nodes which are subcooled region, saturated region and superheated region are applied to OTSG dynamic model.

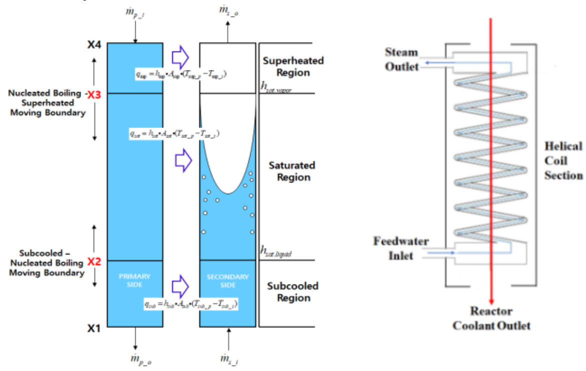

Fig.1 Schematic of the OTSG Dynamic Model

This model is utilized as an OTSG dynamic module (Fig.2). It will be coupled with the primary and secondary components to construct an SMR dynamic model.

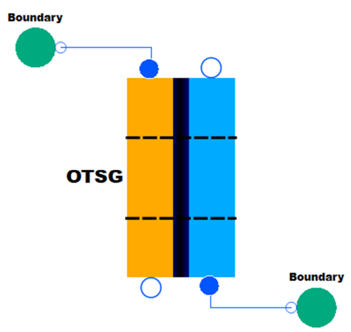

Fig. 2 Modelica OTSG Dynamic module

The dynamic model of OTSG has been formulated by using conservation equations and various heat transfer correlations. The conservation equations applied to the OTSG dynamic model are as follows.

- Mass Conservation Equation

$$\frac{d}{dt}\left[\int_{x_i}^{x_{i+1}} \rho dz\right]-\left[\rho_{i+1}\frac{dX_{i+1}}{dt}-\rho_i\frac{dX_i}{dt}\right]+(\rho v)_{i+1}-(\rho v)_i=0$$

- Energy Conservation Equation

$$\frac{d}{dt}\left[\int_{x_i}^{x_{i+1}} (\rho h-P)dz\right]-\left[\rho_{i+1}h_{i+1}\frac{dX_{i+1}}{dt}-\rho_i h_i\frac{dX_i}{dt}\right]+$$
$$\left[P_{i+1}\frac{dX_{i+1}}{dt}-P_i\frac{dX_i}{dt}\right]+(\rho v h)_{i+1}-(\rho v h)_i$$
$$=(Q_{in}-Q_{out})(X_{i+1}-X_i)$$

- Pressure Drop Equation

$$P_{i+1}=P_i-\rho g(X_{i+1}-X_i)-\frac{1}{2}f\left(\frac{(X_{i+1}-X_i)}{D}\right)\rho v^2$$

where,

X	boundary position of thermohydraulic States
ρ	fluid density [kg/m^3]
v	fluid velocity [m/s]
h	specific enthalpy [J/kg]
P	pressure [Pa]
Q_{in}	inflowed heat from convection [W]
Q_{in}	outflowed heat from convection [W]
g	gravitational constant [m/s^2]
f	friction factor

The heat transfer correlations are identically adopted as the previous steady-state model [5]. Zhu-Kauskas correlation is applied to the primary (shell) heat transfer. Mori-Nakayama, Chen, Modified Bishop Correlation is applied to subcooled, saturated, superheated region in secondary side (tube), respectively.

3. Numerical Demonstration

3.1 Validation of the Dynamic OTSG Model

The previously conducted results of the Modelica Steady-state model [3], MARS-KS [4] benchmark model and the ONCESG [5] code results are compared to validate the Modelica OTSG dynamic model in steady-state. Fig.3 presents the result of the steady-state time history result for SMART steam generator. The primary and secondary coolant temperatures and the internal and external temperatures of the helical tube are presented. After 50 seconds, it can be confirmed that the temperature gradient between primary side, tube and secondary side are constant, and the steam generator is in steady-state.

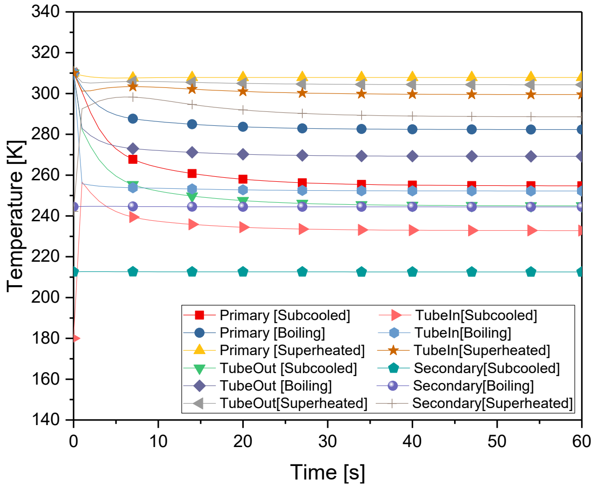

Fig.3. Time History Result for SMART Steady State

Fig.4 and Fig.5 present the analysis result of the MRX and SMART steam generators, respectively. The temperature profile result of the Modelica dynamic model shows similar trend compared to the results of the Modelica steady-state model, MARS-KS and ONCESG code. The boundaries of heat transfer region and coolant temperature are predicted similarly.

While, in the Modelica steady-state model result of the MRX OTSG, the temperature increased rapidly in the superheated steam region and the outlet steam temperature is overestimated compared to other results. But the dynamic model developed in this study presents a small difference of the outlet steam temperature comparing with the results of the MARS-KS and OTSG (Fig.4).

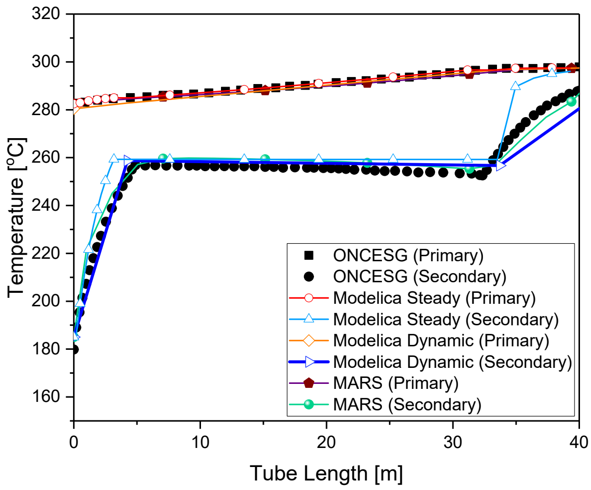

Fig.4. Temperature Profile of MRX OTSG

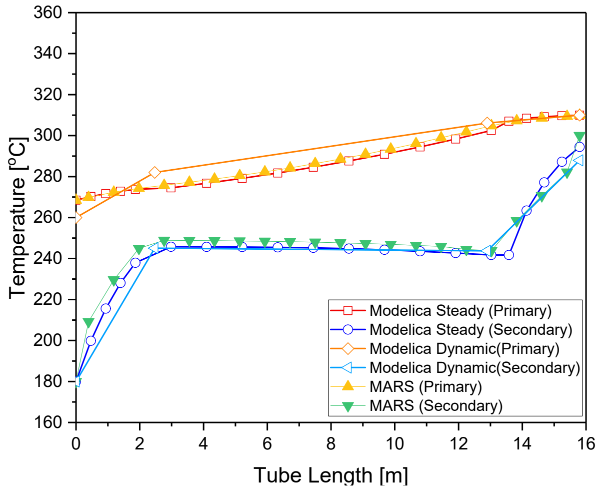

Fig.5. Temperature Profile of SMART OTSG

Table I and Table II present the results of heat transfer boundary and steam outlet temperature for MRX and SMART steam generator. The results of the Modelica dynamic model are similar to other each simulation result, and there is no particular difference.

The Modelica steady-state model overestimates the temperature of the superheated steam region but this is improved in dynamic model.

Table I. The results of the heat transfer region boundary for MRX Steam Generator

Data / Calculation Result	Subcooled - Boiling Boundary [m]	Boiling - Superheated Boundary [m]	Steam Outlet Temperature [℃]
ONCESG	4.88	32.5	287
Modelica Steady	3.17	33.52	296
Modelica Dynamic	4.24	33.70	282
MARS- KS	5.05	31.31	288

Table II. The results of the heat transfer region boundary for SMART Steam Generator

Data / Calculation Result	Subcooled - Boiling Boundary [m]	Boiling - Superheated Boundary [m]	Steam Outlet Temperature [℃]
Modelica Steady	1.59	10.89	294.46
Modelica Dynamic	2.47	12.90	287.91
MARS-KS	1.98	12.25	282.16

3.2 Transient Analysis of the OTSG dynamic model

Transient analysis is conducted using Modelica OTSG Dynamic model. When the temperature perturbation on primary side occurs in steam generator, the steam temperature on the secondary side is examined.

Fig.6 presents the secondary outlet steam temperature according to the primary inlet temperature compared with the MARS analysis results. The result of the Modelica dynamic model presents the similar trend compared to the MARS-KS. But the steam temperature change in secondary side is underestimated compared to MARS-KS.

Fig.7 presents the change of the heat transfer boundary according to the primary inlet temperature. It presents that the secondary temperature increases and the superheated region is wider as the primary inlet temperature increases.

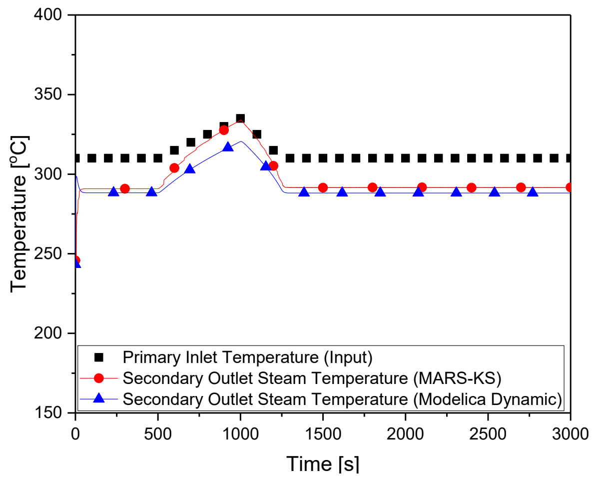

Fig.6. Secondary Outlet Steam Temperature according to Primary Temperature

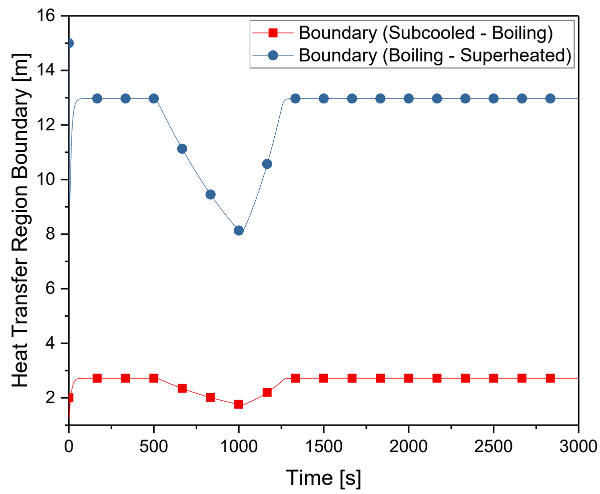

Fig.7. The Position of the Heat Transfer Boundary Change according to Primary Temperature

5. Conclusions

Modelica dynamic model has been developed and benchmarked with ONCESG analysis data and MARS-KS calculation results. MARS-KS has been shown excellent accuracy compared to experimental data.

Modelica results show the acceptable results for estimating the locations of heat transfer transitions.

The developed Modelica model will be utilized to SMR model in NRHES and improved with further investigation and development. This will be the basis of the dynamic model of OTSG which will be developed and incorporated into the NRHES M&S.

ACKNOWLEDGEMENT

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