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

Youngsuk Bang [a*], Keon Yeop Kim [a], So Eun Shin [a], Yeon Jun Choo [a], Sung-Kyun Zee [a]
[a] *Future and Challenge Tech. Co. Ltd., Heungdeok1ro 13, Yeongdeok-dong, Giheung-gu, Yongin-si, Gyeonggi-do*
[*] *Corresponding author: ysbang00@fnctech.com*

## 1. Introduction

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. [1] 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) [2]. In the shell side, the heat from the core would be delivered by the primary coolant. The heat would be transferred to the secondary side inside of the helically coiled tubes. The feedwater would be vaporized and superheated flowing through the tubes. Note that 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. Thus, the integrated analysis should be conducted via multi-physics and multi-scale modeling and simulation (M&S) [3]. Though, several design calculation tools have been developed for a specific component or phenomena, coupling those tools would not be viable without source code modification. Because of its complexity and large-scale, the integrated analysis model should exploit the reduced order approach to make the computation feasible and practical.

In this study, the heat transfer in helical coiled OTSG has been investigated and Modelica computation module has been developed. The mathematical formulation has been derived by using the moving boundary approach and implemented by using OpenModelica environment [4]. The MARS-KS model [5] has been also developed to benchmark/validate the calculation results of the developed Modelica model.

## 2. Modelica Model Development

The simple steady-state model has been formulated by using conservation equations and equations of states. The steam/water properties are calculated by using functions of Media.Water.IF97_Utilities in Modelica Standard Library. The basic equations are presented in Eq. (1) ~ Eq. (5).

○ Mass Conservation

$$W_{x,i} = W_{x,i+1} \tag{1}$$

○ Energy Conservation:

$$H_{P,i+1}W_{P,i+1} - H_{P,i}W_{P,i} = HTC_{P,i}A_{P,i}\left(T_{P,i} - T_{M,i}\right) \tag{2}$$

$$H_{S,i+1}W_{S,i+1} - H_{S,i}W_{S,i} = HTC_{S,i}A_{S,i}\left(T_{M,i} - T_{S,i}\right) \tag{3}$$

○ Pressure Drop:

$$\Delta P_{x,i} = \Delta P_{x,i,g} + \Delta P_{x,i,f} + \Delta P_{x,i,a} \tag{4}$$

○ Equation of State:

$$T_{x,i} = ASME\left(P_{x,i}, H_{x,i}\right) \tag{5}$$

where,

| | |
|---|---|
| $x$ | $P$ for primary side, $S$ for secondary side, |
| $W_{x,i}$ | mass flowrate in control volume (CV) $i$ |
| $H_{x,i}$ | specific enthalpy in CV $i$ |
| $\Delta P_{x,i}$ | pressure drop in CV $i$ |
| $\Delta P_{x,i,g}$ | gravitational pressure drop in CV $i$ |
| $\Delta P_{x,f}$ | frictional pressure drop in CV $i$ |
| $\Delta P_{x,a}$ | accelerational pressure drop in CV $i$ |
| $A_{x,i}$ | heat transfer area in CV $i$ |
| $T_{x,i}$ | Temperature in CV $i$ |
| $P_{x,i}$ | Pressure in CV $i$ |
| $HTC_{P,i}$ | heat transfer coefficient in CV $i$<br>(primary coolant to tube wall) |

$HTC_{s,i}$ heat transfer coefficient in CV $i$ (tube wall to secondary coolant)

Heat transfer coefficients and pressure drop correlations are adopted from Ref. [6]. It is important to note that the specific enthalpy at the interfaces of subcooled region – boiling region and boiling region – superheated region are specified as the liquid saturation enthalpy and vapor saturation enthalpy, respectively. Therefore, the location of the interfaces would be explicitly calculated as unknowns.

## 3. MARS-KS Modeling for Benchmarking

MARS-KS models of OTSGs for MRX and SMART have been developed for benchmarking Modelica models. The design data of the steam generator are referred from Ref [6]. Figure 1 presents the schematic and the nodalization of the MARS-KS model.

In order to find an appropriate model for predicting accurate temperature profiles on the primary and the secondary sides of the steam generators, the sensitivity analysis with various number of nodes are performed.

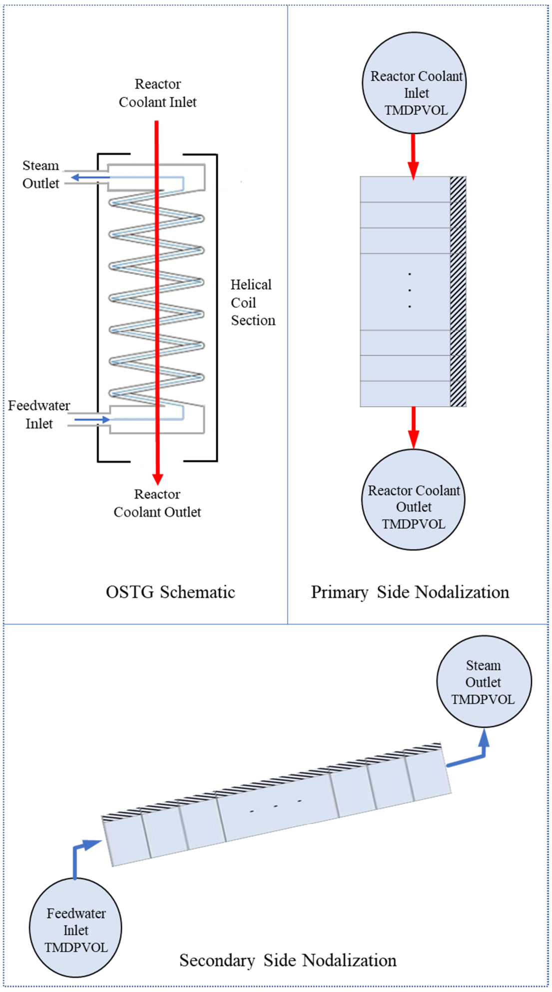

Fig.1. Schematics of OTSG MARS-KS model

## 4. Numerical Experiments

The MARS-KS benchmark analysis result and the ONCESG code result are compared to validate the Modelica OTSG model, Figure 2 presents the analysis result of the MRX steam generators.

The temperature profile result of Modelica model shows similar trend compared to the results of MARS-KS and ONCESG code, except for overestimating in the secondary superheated steam region.

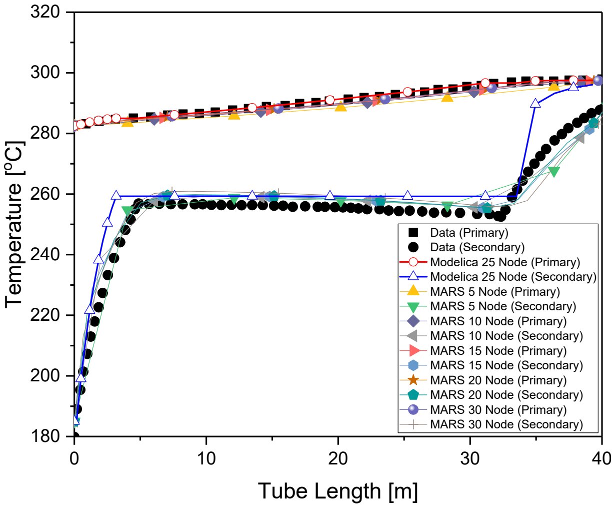

Fig.2. Temperature Profile Comparison of MRX OTSG

Table 1 shows the results of heat transfer boundary between subcooled, nucleate boiling, and superheated steam regions for MRX Steam generator. The differences between the Modelica analysis results and the ONCESG results are evaluated within 3%. In the MARS-KS analysis, as the more nodes are used, the differences to ONCESG code results are decreased. With more than 20 nodes, the differences are predicted within 3% ranges. Table 2 shows the results of heat transfer boundary for the SMART Steam generator. The Modelica model and the MARS-KS model showed similar results.

Table.1. The result of the heat transfer region boundary for MRX Steam generator

| Data / Calculation Result | | Subcooled - Nucleate Boiling Boundary | | Nucleate Boiling - Superheated Boundary | |
|---|---|---|---|---|---|
| | | Length [m] | Difference [%] | Length [m] | Difference [%] |
| ONCESG | | 4.88 | - | 32.5 | - |
| Modelica | | 4.64 | 0.6 | 33.52 | 2.5 |
| MARS -KS | 5 Node | 4.04 | 2.1 | 28.30 | 10.4 |
| | 10 | 6.06 | 2.9 | 30.03 | 6.1 |
| | 15 | 6.73 | 4.6 | 33.66 | 2.9 |
| | 20 | 5.05 | 0.4 | 31.31 | 2.9 |
| | 30 | 4.71 | 0.4 | 32.99 | 1.2 |

Table.2. The result of the heat transfer region boundary for SMART steam generator

| Data and Calculation Result | | Subcooled - Nucleate Boiling Boundary [m] | Nucleate Boiling - Superheated Boundary [m] |
|---|---|---|---|
| Modelica | | 1.59 | 10.89 |
| MARS-KS | 5 Node | 1.58 | 11.06 |
| | 10 Node | 2.37 | 13.85 |
| | 15 Node | 2.63 | 13.16 |
| | 20 Node | 1.98 | 12.25 |

## 5. Conclusions

Modelica model has been developed and benchmarked with experimental 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 validated and improved with further investigation and development. The up-to-date correlations will be examined. 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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