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Development of a Balance-of-Plant System Simulation Model for Small Modular Reactors Using OpenModelica

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1. Introduction

South Korea is actively developing i-SMR, a small modular reactor that retains the advantages of conventional nuclear power while significantly enhancing safety. Additionally, to expand the flexibility of nuclear power plants, the design allows for not only a base load operation but also load-following and multipurpose utilization.

Load-following enables the reactor's electrical output to be adjusted according to grid demand. In contrast, multipurpose utilization involves the direct use of steam from the steam generator for thermal energy applications instead of electricity generation. The stored thermal energy can be utilized for various industrial processes such as seawater desalination, district heating, and additional power generation as needed. These innovative technologies help compensate for the intermittency of renewable energy sources while ensuring a stable power supply.

To implement load-following and multipurpose utilization, direct integration with the BOP system, including the turbine and feedwater system, is required. Therefore, this study aims to develop a BOP system model using OpenModelica. Through the development of this model, we aim to provide a simulation framework for the analysis of the operational characteristics of i-SMR under the flexible analysis.

2. i-SMR BOP modeling based on OpenModelica

2.1 OpenModelica

OpenModelica is an equation-based, object-oriented programming language that enables efficient modeling and simulation of complex physical systems. It is widely used in industrial sectors that require multiphysics analysis, such as fluid-mechanical-electrical interactions in nuclear power plant secondary system modeling. In this study, an improved version of the open library ThermoPower [1] was utilized to develop a secondary system model.

2.2 Component modeling of BOP

The secondary system of i-SMR consists of the main steam, condensate and feedwater, and turbine systems, which convert the thermal energy produced by steam generators (SGs) into electrical energy. A schematic diagram of the basic design of i-SMR secondary system is shown in Figure 1.

The main steam system supplies the steam generated in the SG to the turbine system, while the turbine exhaust steam is directed to the feedwater heater to enhance feedwater temperature and improve secondary system efficiency. The condensate and feedwater system supplies the required temperature, pressure, and mass flow rate of feedwater to the steam generator through the feedwater heater and pumps (condensate and feedwater pumps).

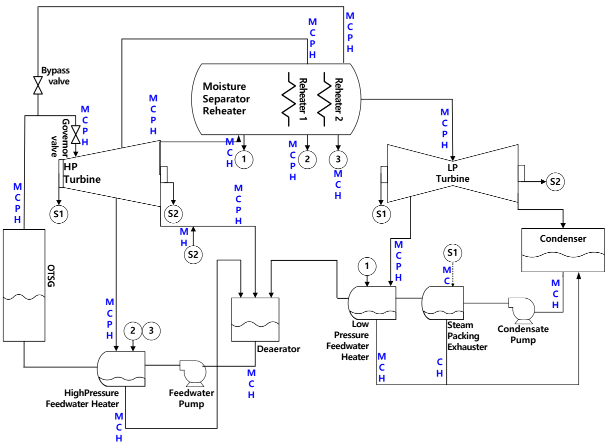


Fig. 1. Balance of Plant Configuration for i-SMR

Below is the governing equation for the major components.

2.2.1 Pipe modeling

The governing equations in the provided OpenModelica code describe the dynamics of a 1D fluid flow model for a two-phase fluid (water/steam) inside a pipe. Below is a summary of the main governing equations that model the fluid flow, heat transfer, and pressure drops within the system:

1) Mass equation

$$A \cdot \ell \left(\frac{\partial \rho}{\partial h} \frac{dh}{dt} + \frac{\partial \rho}{\partial P} \frac{dP}{dt} \right) = \dot{m}_{in} - \dot{m}_{out}$$

This equation ensures that the total mass flow into the pipe is equal to the mass flow out of it.

2) Momentum equation

$$\frac{\ell}{A}\cdot\frac{dw}{dt}+(P_{in}-P_{out})+Dp_{stat}+Dp_{fric}=0$$

Here, w is the mass flow rate, P_{out} and P_{in} are the pressure at the outlet and inlet, Dp_{stat} is the pressure drop due to static head, and Dp_{fric} is the pressure drop due to friction.

3) Energy equation

$$A\cdot\ell\cdot\rho\cdot\frac{dh}{dt}+w\cdot(h_{out}-h_{in})-A\cdot\ell\cdot\frac{dP}{dt}=Q_{source}$$

Here, h represents the specific enthalpy, and Q is the heat flow into the volume.

4) Wall heat transfer equation

$$A_w\cdot\ell\cdot\rho_w\cdot\frac{dT_{w,vol}}{dt}=Q_{in}-Q_{out}$$

Where, $T_{w,vol}$ represents the volume temperature of the tube, Q_{in} and Q_{out} is the heat conduction rates on the internal and external surfaced, respectively. Subscript 'w' means wall.

2.2.2 Tank modeling

The tank model was developed to simulate heat transfer phenomena occurring within a large volume such as Condenser and deaerator. This component was formulated as a zero-dimensional (0-D) model, considering only mass and energy equations. Additionally, in cases where heat pipes are present, such as in feedwater tubes, the tank model tracks water level to distinguish between two-phase and single-phase heat transfer regions. Although the model is highly simplified, it closely resembles the TANK component of MARS-KS [4] in its analysis methodology.

1) Mass equation

$$\frac{dM}{dt}=w_s-w_c$$
$$(M=V_l\cdot\rho_l+V_s\cdot\rho_s)$$
$$(V=V_l+V_s)$$

Where, w_s is the steam mass flow rate, w_c is the condensate mass flow rate, M is mass, and V is Volume. Subscript 'l' is liquid phase and 'v' means vapor phase.

2) Energy equaiton

$$\frac{dE}{dt}=w_s\cdot w_s+(P_{in}-P_{out})+Dp_{stat}+Dp_{fric}=0$$
$$(E=M_l\cdot h_l+M_v\cdot h_v-p\cdot V)$$

Here, w is the mass flow rate, P_{out} and P_{in} are the pressure at the outlet and inlet, Dp_{stat} is the pressure drop due to static head, and Dp_{fric} is the pressure drop due to friction.

2.2.3 Turbine modeling

To predict the pressure drop due to variations in turbine mass flow rate, the widely used Stodola's law (also known as the Ellipse law) was applied. Stodola's law is a fundamental thermodynamic equation that describes the relationship between turbine mass flow rate and pressure and is particularly useful for simplifying the modeling of steam or gas flow through nozzles or turbines. The governing equation of Stodola's law is given as:

$$\mathrm{w}=k_t\cdot\sqrt{P_{in}\rho_{in}}\sqrt{1-\left(\frac{P_{in}}{P_{out}}\right)^2}$$

Here, k_t is the coefficient of Stodola's law.

The turbine's design efficiency was assumed to be the isentropic efficiency, as given by:

$$\eta=\frac{h_{in}-h_{out}}{h_{in}-h_{out,s}}$$

Here, $h_{out,s}$ is the isentropic enthalpy of turbine outlet.

In addition, mechanical power is calculated as shown in the following equation, and torque and rotational speed are calculated in combination with flow rate and enthalpy.

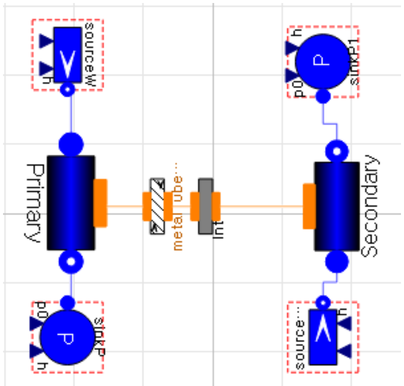
$$P_m=\eta_{mech}\cdot\mathrm{w}\cdot(h_{in}-h_{out})=-\tau\cdot\varphi$$

Here, η_{mech} is turbine mechanical efficiency, τ is torque, and φ is turbine angular velocity

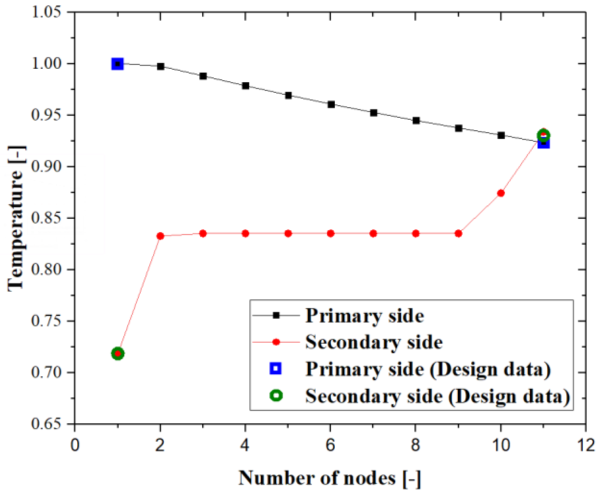
2.2.4 Steam generator modeling

The steam generator modeling employed the pipe modeling approach described in Section 2.2.1. To accurately simulate heat transfer phenomena within the steam generator, an additional heat transfer coefficient model for the helical coil was incorporated. The shell-side heat transfer of the primary system was modeled using the Zukauskas equation [2], while the tube-side heat transfer of the secondary system applied the Mori-Nakayama correlation [3].

To assess the accuracy of the heat transfer prediction in the steam generator, a separate input model for the helical coil steam generator was developed. Fig. 2(a) illustrates the OpenModelica steam generator model, while Fig. 2(b) presents the temperature behavior of the primary and secondary sides of the helical coil steam generator. The steam generator was modeled with a total of 11 nodes, and the calculated results were compared with the basic design data at the inlet and outlet of both the primary and secondary sides. The comparison showed an error within 1%, indicating high accuracy. Additionally, the secondary exhibited distinct subcooled, saturated, and superheated regions, confirming proper phase transition characteristics.



(a) Helical coil steam generator modeling



(b)Temperature behavior

Fig. 2.Evaluation of Helical-coil steam generator heat transfer prediction

2.2.5 Feedwater heater modeling

The shell-side of the feedwater heater and the condenser was modeled using the tank model described in Section 2.2.2, while the tube-side employed the pipe model. Currently, the tube-side heat transfer was modeled using the Dittus-Boelter correlation. However, the condensation process on the shell side does not have its own condensation model and instead uses a constant heat transfer coefficient. Afterwards a condensation model will be added in the heat transfer package.

2.3 BOP modeling for i-SMR

The Fig 3 shows i-SMR BOP input model developed using OpenModelica. All major components included in the BOP have been modeled, and a PID control logic has been added to regulate the feedwater flow rate. Additionally, generator and grid models have been incorporated to calculate the power output to the electrical grid.

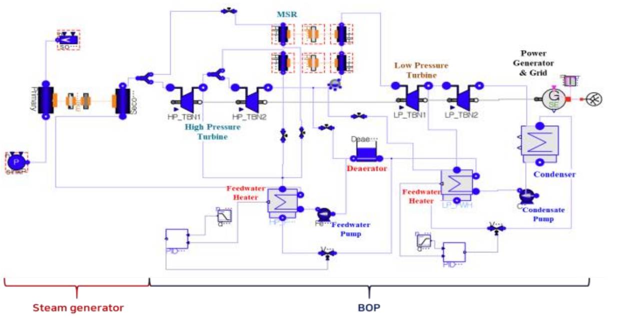


Fig. 3. Schematic diagram of BOP modeling for i-SMR (Basic design)

3. Simulation results

Figs. 4–7 compare the basic design data of i-SMR with the OpenModelica simulation results. Fig. 4 shows the turbine power output, which converged well within approximately 800 seconds, with an error of about 5%. This discrepancy is further analyzed in Fig. 5, which presents the mass flow rate through major BOP components. The results indicate that the flow rate at the turbine outlet is higher than the basic design data. The results indicate that the flow rate at the turbine outlet is higher than the basic design data. This overestimation occurs because the extraction steam flow from the turbine is underpredicted, leading to an overestimated turbine power output. On the other hands, the feedwater pump flow was accurately predicted.

Fig. 6 presents the pressure distribution across major BOP components. It was observed that the pressure drop in the high-pressure turbine was overestimated, while the pressure values in other components remained stable and within reasonable deviation from the reference data. The results in Figures 5 and 6 show that the turbine input model needs to be improved. Therefore, various formulations of Stodola's law will be explored to enhance the turbine model.

Fig. 7 shows the temperature distribution across major BOP components. Due to the underestimation of extraction steam flow, the feedwater temperature was predicted to be slightly lower than the basic design data. However, the overall temperature trends closely aligned with the design data, demonstrating the model's general accuracy.

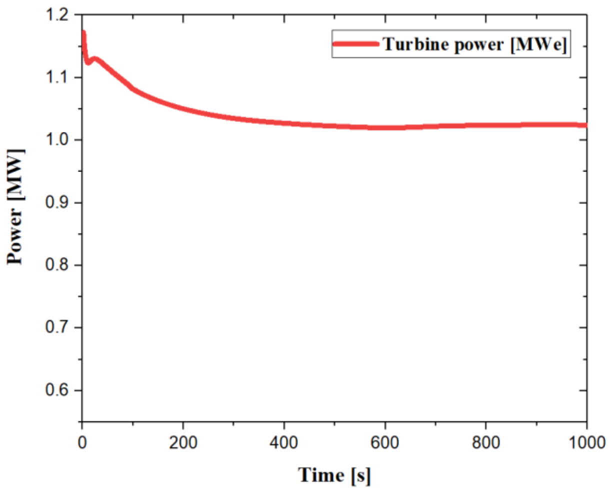


Fig. 4. Turbine power of i-SMR (Basic design)

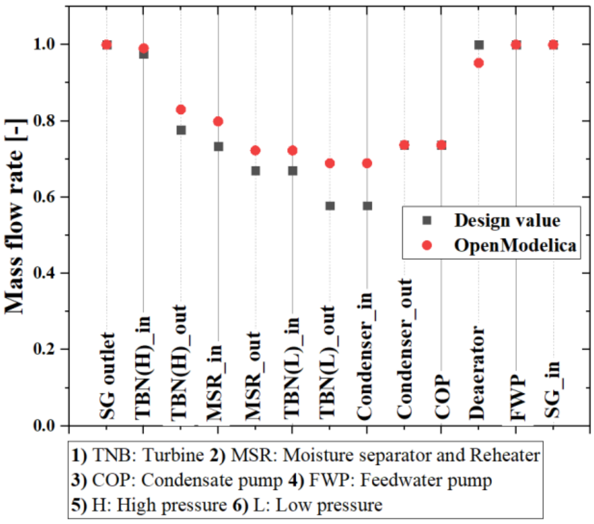


Fig. 5. Mass flow rate of major components in BOP (Basic design)

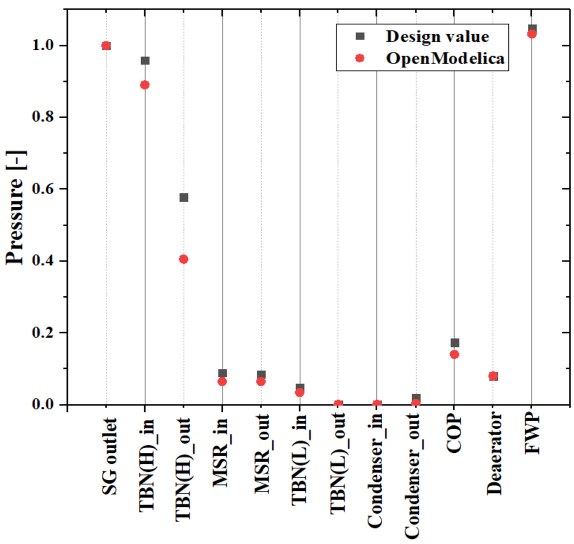


Fig 6. Pressure of major components in BOP (Basic design)

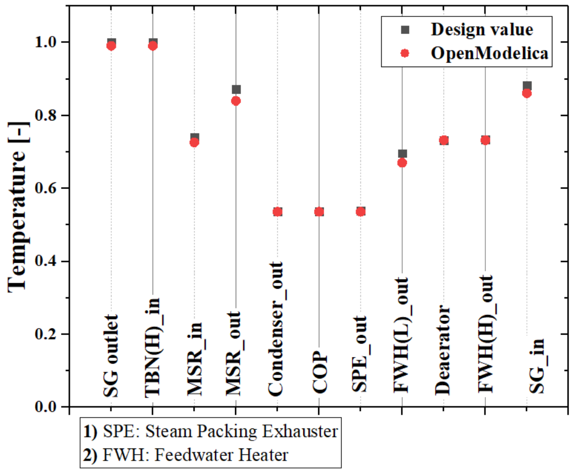


Fig 7. Temperature of major components in BOP (Basic design)

4. Conclusions

In this study, an input model for the BOP for i-SMR was developed using the OpenModelica code. A modeling methodology was established for fluid components such as turbines, feedwater heat exchangers, and deaerators, which are not typically addressed in traditional nuclear power plant safety analyses.

To verify the code, i-SMR basic design data were compared with the simulation results. While improvements are needed to enhance the accuracy of pressure drop predictions in the turbine and extraction steam flow rates, the model effectively covered the overall trends in flow rate, pressure, and temperature across major BOP components.

Future work will focus on refining the input model to improve computational reliability. In addition, to analyze the flexible operation of i-SMR, an integrated model will be developed that simultaneously simulates both the primary system and the BOP system of the nuclear power plant.

ACKNOWLEDGMENTS

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