Modeling of Steam Power Conversion System for APR1400 using MARS-KS

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1. Introduction

The concept of a Nuclear-Renewable Hybrid Energy System (NRHES) is to combine a nuclear power plant (NPP) with renewable energy to improve efficiency and economy of energy as shown in Figure 1 [1]. Currently, the design concept for NRHES is being actively studied for Small Module Reactor (SMR) [2-3]. However, with the increase in the generation rate of renewable energy sources and the demand to increase the efficiency of NPPs, it is necessary to consider the NRHES research for large NPPs as well.

In the case of large NPPs, load-following operation is not applied, thus, a method of extracting the steam generated by the steam and power conversion system (SPCS) can be utilized. However, steam extraction through the SPCS may cause unexpected thermodynamic perturbation of main components. In addition, by utilizing the thermal energy of the nuclear power plants to the NRHES, the feedwater temperature flowing into steam generators is decreased, i.e., it can affect the core reactivity.

Accordingly, it is required to study a design method that can minimize the safety degradation of nuclear power plant with improving the efficiency.

In this paper, we modeled the SPCS for APR1400 to analyze the thermodynamic behavior of secondary systems using MARS-KS code. To develop the SPCS model, we used the heat balance diagram under Valve Wide Open (VWO) condition in Final Safety Analysis Report (FSAR) of APR1400.

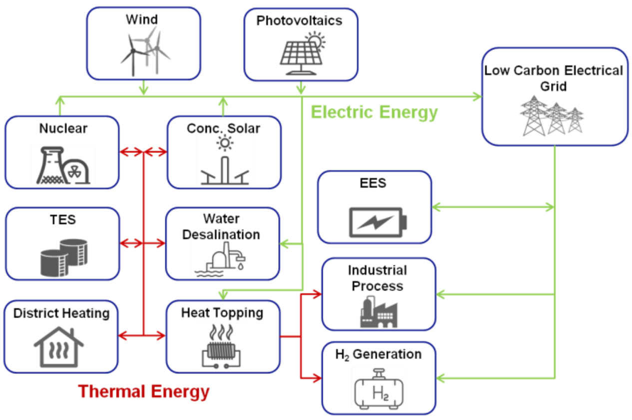

Figure 1. Conceptual diagram for the Nuclear-Renewable Hybrid Energy System

2. Steam and power conversion system modeling description

To develop the analysis model for SPCS of APR1400, we consider the various major components such as steam generators (SGs), high-pressure turbine (HPT), moisture separator (SEP), 2-stage re-heater (RH), low-pressure turbine (LPT), condenser (CD), Steam Seel Regulator (SSR), Steam packing exhauster (SPE), condensate pump (COP), 3-stage low-pressure feedwater heaters (LFHs), Deaerator (DE), feedwater booster pump (FBP), feedwater pump(FWP) and 3-stage high-pressure feedwater heaters (HFHs) as shown Figure 1.

2.1 Analysis model setup

The nodalization for SPCS modeling is represented in Figure 2.

2.1.1 Turbine modeling

For modeling the turbine, we used the turbine model built-in MARS-KS code [4]. In APR1400, steam at about 50 bar is reduced to about 0.08 bar as it passes through turbines, and the pressure drop at turbines is converted into the turbine work. Therefore, the prediction of rapid pressure drop is important to calculate the turbine work. In MARS-KS, the pressure drop and turbine work in turbine are calculated as follows;

Equation (1) represents the energy balance equation of the turbine component to calculate the turbine work.

○ Prototype energy balance equation in turbine components

$$\left[\rho v A\left(\frac{1}{2}\right)v^2 + h\right]_{in} = \left[\rho v A\left(\frac{1}{2}\right)v^2 + h\right]_{out} + (\rho v A)_{in} W = \left[\rho v A\left(\frac{1}{2}\right)v^2 + h\right]_{out} - (\rho v A)_{in} \cdot \eta \frac{1}{\rho}\Delta P \quad (1)$$

$* \, dh = \frac{1}{\rho} dP$ (Isentropic condition)

Where,

ρ	Fluid density in control volume (CV)
v	Fluid velocity in CV
A	Area in CV
h	Fluid enthalpy in CV
W	Turbine work
η	Turbine efficiency
ΔP	Pressure drop though the turbine components

By substituting the pressure drop relationship in Equation (1) into the pressure gradient term of the momentum equation, the vapor momentum differential equation in the turbine can be obtained as shown in Equation (2).

○ Vapor momentum differential equation in turbine components [5]

$$(\alpha_v \rho_v)\left(\frac{\partial v_v}{\partial t} + v_g \frac{\partial v_v}{\partial x}\right) = -\alpha_v (1-\eta)\frac{\partial P}{\partial x} - \alpha_v \rho_v v_v HLOSSG - \\ -\alpha_v \rho_v FIG(v_v - v_l) \qquad (2)$$

Where,

α	Void fraction in CV
v	Fluid velocity
$HLOSSG$	From or fictional losses of vapor
FIG	Interphase drag coefficients of vapor

It was confirmed that the pressure drop due to the kinetic energy change was considered while passing turbine.

HPT and LPT were divided into four and five volumes to consider the extraction line, respectively. At each extraction line, the high-temperature steam was discharged into a heat exchanger (e.g. re-heaters, feedwater heat exchangers, and deaerator) to improve the plant efficiency.

2.1.2 Feedwater heat exchanger modeling

In the case of feedwater heaters (FWHs), it effectively increases the feedwater temperature by utilizing the condensation heat transfer of steam flowing in from the turbine on the shell side. In order to predict the performance of FWH, it is important to consider the pressure drop and the water level along the FWH. For example, if the pressure drop is lowered, the steam flow rate flowing into the downstream FWH may be decrease. Also, if the water level of FWH accumulates excessively, the outlet temperature of feedwater is decreased.

First of all, the feedwater heaters were modeled as simplified two horizontal pipes. Considering the horizontal structure of the heat exchanger, the Churchill-Chu model was used for the convection heat transfer model [6].

2.1.3 Other equipment modeling

The shell side of the steam generator was modeled using pipe components. The heat rate transferred from the reactor coolant system was modeled using the virtual heater component instead of complex reactor coolant system modeling.

The moisture separator reheater (MSR) was modeled using pipe components.

In the case of the condenser, two vertical pipes were modeled to prevent thermal stratification. The pressure of the condenser was maintained by time-dependent volume. Also, the seawater circulation system for condensing the steam supplied to condenser was modeled using the time-dependent volumes and time-dependent junction.

The main purpose of the deaerator is to mix the fluid flowing in from various lines, i.e., it is a mixed heat exchanger. Therefore, it was modeled with two vertical pipes to simulate the proper mixing phenomenon. The pressure of the deaerator was maintained by time-dependent volume.

The pumps such as COP, FBP, and FWP were modeled using the Westinghouse pump model built-in MARS-code.

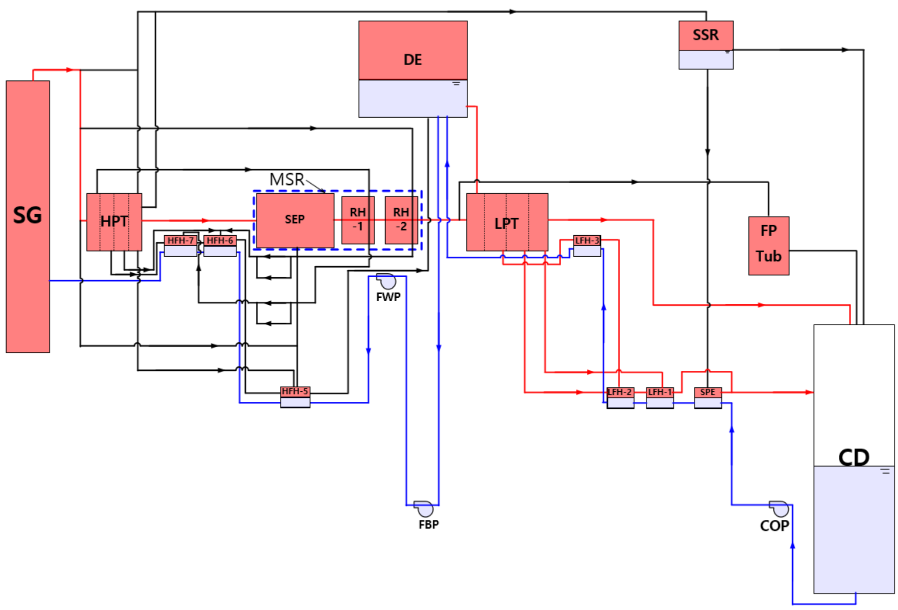

Figure 2. Schematic of the SPCS for the APR1400

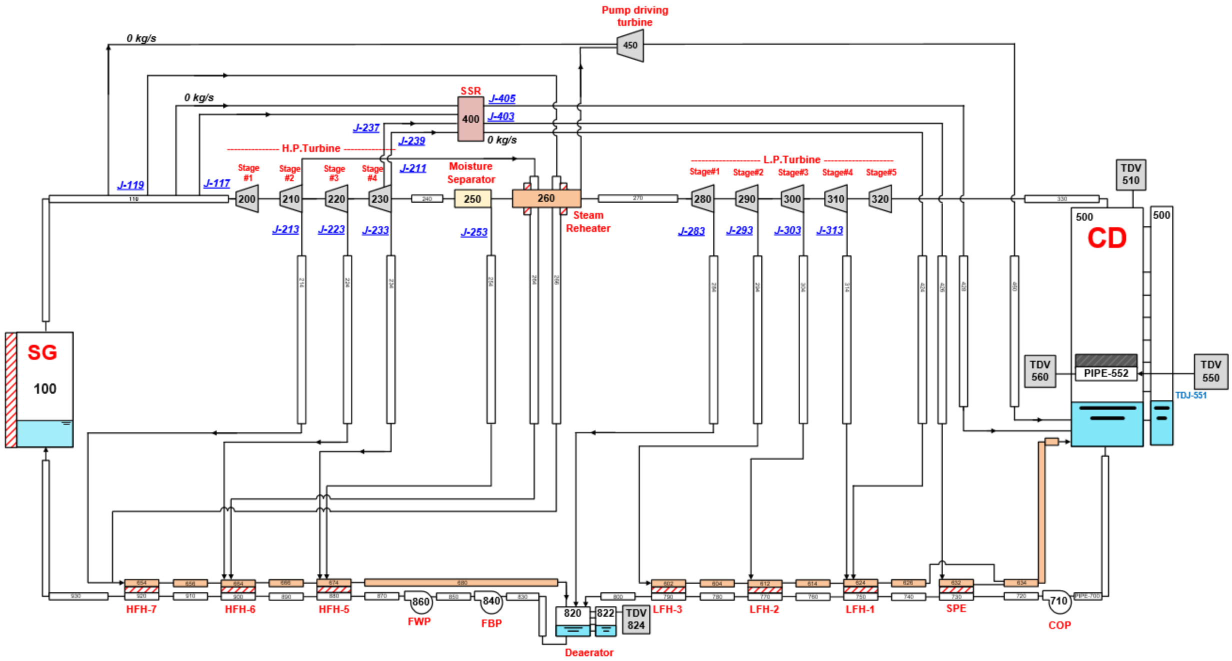

Figure 3. MARS-KS nodalization for the SPCS of APR1400

2.2 SPCS modeling validation

To validate the SPCS modeling, the calculation results were compared with the heat balance diagram at VWO in FSAR of APR1400 [7].

Figures 3 and 4 show the pressure and temperature of the main components, respectively. The obtained results predict the behavior of the SPCS well along with the main components. Figures 5 and 6 represent the mass flow rate in the main and extraction lines.

It was confirmed that the flow rate of the main line was almost identical to the plant data, while the flow rate of the extraction lines was predicted to be slightly low. As mentioned above, it is important to predict the pressure drop of FWH well. However, since the current modeling of FWH was modeled using horizontal pipe, there was a limit to reflect the complicated figuration of FWH, i.e, the pressure drop was predicted to be very low. To match the pressure drop, the loss coefficient must be increased immoderately, however, it cause excessive accumulation of condensed water. Therefore, we will have the plan to use 'MULTID' component to consider the FWH shape and to satisfy the thermo-hydraulic conditions.

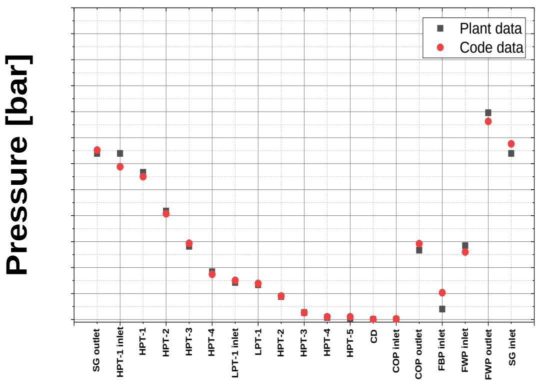

Figure 4. Comparison of pressure behavior along with the main components

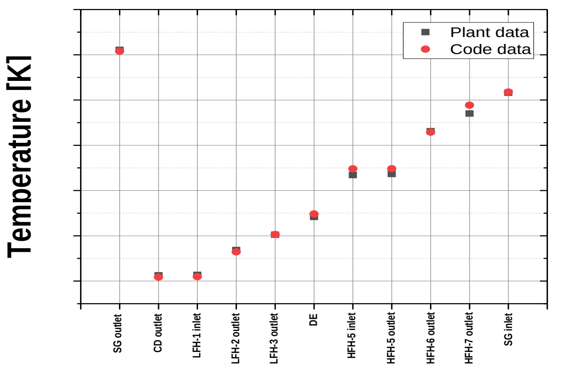

Figure 5. Comparison of temperature behavior along with the main components

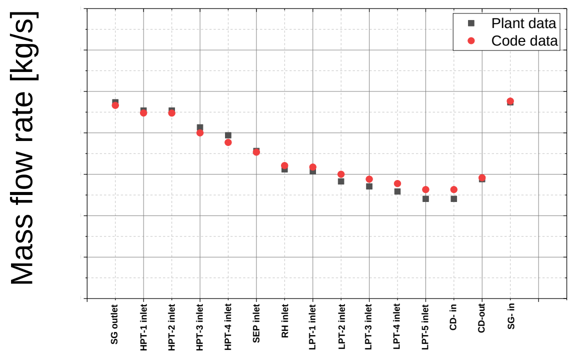

Figure 6. Comparison of mass flow rate along the mainline

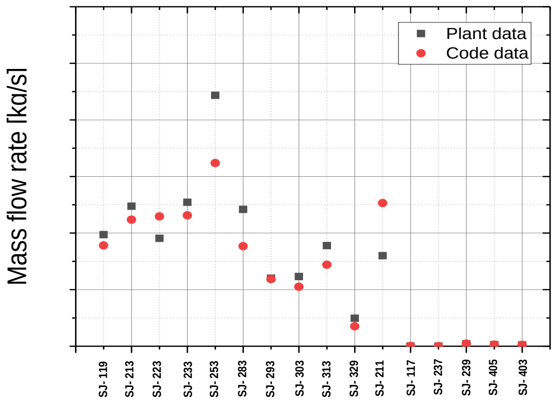

Figure 7. Comparison of the mass flow rate of extraction line

3. Conclusion and Future work

In this paper, the SPCS for APR1400 was modeled by using MARS-KS code. The SPCS is a complicated system including fluid equipment (e.g. turbine, FWH, pump, etc.) under the two-phase flow condition with a pressure change of about 50 to 0.08 bar.

The main purpose of SPCS modeling is to predict pressure drop, flow distribution, and fluid temperature data for major compartments. Although continuous improvement is needed, it was confirmed that the calculated results were in agreement with heat balance diagram data at VWO of FSAR.

Based on the developed modeling, we will analyze the dynamic behavior of SPCS caused by the operation of NRHES or the accident of the secondary system.

Although the developed model is based on the APR1400, the analysis method can be utilized for various nuclear power plant types.

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