Secondary System Modeling Guideline in Use of MARS-KS Code for Nuclear Renewable Hybrid Energy Systems

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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 [1]. In the coupling of NRHES to the secondary system of a nuclear power plants (NPP), it is important to evaluate the effect on the secondary system operating parameters caused by the operation of NRHES.

For this reason, the authors have developed input modeling of the MARS-KS code [2] required for the analysis of the thermal hydraulic performance and behavior of the plant secondary system since 2021 [3, 4, 5, 6]. However, modeling of systems that implement the desired performance was not easily accessible, since complex two-phase flow phenomena are involved. For example, condensation in feedwater heaters (FWH) shell side and heat transfer to the tube side, the related pressure drops in shell side and tube side should be appropriately implemented to meet the desired performance of FWH. Conversion of pressure difference to mechanical energy in turbines are also involved in this problem.

For that reason, and because of its relatively low importance in terms of safety, it seems that modeling and analysis of secondary systems using system thermal-hydraulic codes has been rarely been attempted. However, it is obvious that the construction and operation of NRHES requires system code analysis of the secondary system.

Developing a modeling for such system code analysis requires a lot of time and effort. This paper aims to provide a guideline to general secondary system modeling using the MARS-KS code. Technical background of the guideline is based on the efforts and experiences of the authors so far. Although there may be some deficiencies or irrationalities because it is hard to say the authors have experienced and solved all the problems of secondary system modeling, we believe they are reasonable in terms of the general modeling direction. Specific contents in this guide are expected to help future potential analysts as well as authors save their time and effort.

2. Major Functional Features

Generally, the secondary system we are concerning has the following major functional features

1) The secondary system operates the turbine using the steam produced by the steam generators (SG), and supplies the feedwater to the SG by heating and pressurizing the condensed water from the condenser (CO).
2) Moisture separator and reheaters (MSR) remove moisture from the steam that has passed through the high-pressure turbine (HPT) and reheats it before entering the low-pressure turbine (LPT), and supplies the condensate generated during this process to the low-pressure FWH.
3) Steams are extracted from the several turbine stages and supplied to the FWH to heat the feedwater.
4) Condensed water is at most produced by condensation in the CO of steam which comes from the last stage of the LPT in a nearly vacuum state.
5) For energy efficiency, condensed water generated on the shell side of one FWH is drained to the sequentially connected FWH.
6) In the Deaerator, condensate drained from the high-pressure FWH, water from the low-pressure FWH, and steam extracted from the HPT are properly mixed to remove noncondensible gas and provide a water source with an appropriate head to the feedwater pumps (FWP).

There are other major functional features, but the considerations in modeling are limited to the above.

3. Guideline

3.1 Overall Configuration

In general, the secondary system is complexly composed of numerous components. It is impossible to consider all components in the system code. Therefore, it is necessary to select only the components that correspond to the purpose of the analysis. For NRHES application, the main steam sources, HPT and LPT, MSR, CO, low and high pressure FWH, Deaerators, condensate pumps (COP), FWP, feedwater provider to SG, and connecting pipes between each component should be selected.

3.2 Modeling of Major Components

<u>Turbines</u>

1) Turbines can be modeled according to the user manual of the MARS-KS code. Turbines should be modeled in several stages according to the steam extraction point.
2) Artificial turbines should be placed at the front end of the HPT and the LPT, respectively, for the stability

of the calculation. Input data for artificial turbines shall be in accordance with the code manual [7].

3) It was pointed out that the energy conservation between the enthalpy at the inlet and outlet of the turbine and the work done for the shaft of the turbine was not satisfied in the previous version of the MARS-KS. When the MARS-KS code was improved at 2021, this problem was solved [8]. Use of the improved code is recommended.
4) For the second junction of the turbine component, the geometry in the crossflow direction (y-direction) should be entered on the ccc1801 card. This card input is described in the recent RELAP5/MOD3.3 code manual [9]
5) The shaft component shall be used to define that the all turbine stages are connected to the shaft and generator. In addition, the shaft component input should describe which situations the generator is synchro or disconnected with the grid.
6) Hydraulic resistances (K-factors) at the junctions of turbine should be determined first by the formula in reference [3] and adjusted according to the turbine efficiency, the required flow rate and pressure.

<u>Pumps</u>

1) Pumps can be modeled according to the user manual of the MARS-KS code.
2) The rated condition of the pumps may be adjusted to match the desired condition if the pump design data is not available.
3) Speed control of FWP and COP can be used for stable calculations, but this can cause problems if other components are not modeled correctly. Therefore, it is recommended to use a constant speed option

<u>Condenser</u>

It is modeled as heat exchanger with horizontal tubes traversing the vertically downward steam flow path to be close to the actual shape. Heat transfer area may be a key factor to be adjusted if the design data is not available. Also, imposing a boundary condition of vacuum pressure should be considered.

<u>Feedwater Heaters</u>

FWH is a typical heat exchanger in the shape of a shell-and-tube. In this type of heat exchanger, many baffle plates are installed to establish the desired flow direction for the efficiency of heat transfer. Therefore, simulating this one in one-dimensional way can cause a lot of complexity. We recommend use of MULTID component for the FWH [4]. Applying the MULTID component has the advantage to get the results relatively close to actual phenomena, although there is a slight disadvantage in computation time.

<u>Deaerator</u>

Deaerator is a long horizontal tank, but its main flow direction is vertical. Steam extracted from the HPT, condensed water drained from the high-pressure FWH, and feedwater passing through the low-pressure FWH are introduced into the deaerator, and then mixed water is flowed to the FWP. For each flow path, the location and orientation to/from the deaerator should be modeled appropriately. For example, the direction of the junction flowing into the deaerator from the high-pressure FWH shall be vertically upward.

<u>Moisture Separator/Reheaters</u>

MSR is a long horizontal tank, also a heat exchanger in which steam pipes pass horizontally inside, and with a moisture collection part at the bottom. In the current modeling, a method of horizontally connecting several vertical pipes through cross-flow junctions is used to take into account the horizontal flow of steam and the vertical flow of condensate. When the specific shape and data of the MSR are available, it is desirable to model using the MULTID component like the case of FWH, but the one-dimensional modeling can be considered reasonable if the calculation results are reasonable.

<u>Connecting pipes</u>

All important components are connected by piping, and in many cases, they can be branched from the component into two or more flow paths, or multiple pipes can be merged into the component. In the authors' experience, in most cases, data on pipes were not available except for pipe diameters. Therefore, when determining the modeling suitable for the required pressure drop and flow rates between the connected components, the effect of the length and shape of the pipe could not be considered, and the only way was to impose hydraulic resistances. In this respect,

1) the modeling of connecting pipes should be as simplified as possible.
2) Differences in elevation of each component should be considered in modeling of the connected pipe, as the elevation at which each component is installed is different and may affect performance.

3.3 Nodalization

System code analysis is to calculate the thermal-hydraulic properties at each node discretized with finite volume, thus the node size (length) should be properly determined. In general, the length of the node may affect the Courant time limit for the stability of the calculation. It is generally recommended not to have a short length unless you track a phenomenon that occurs in a small section in a short time, such as a water hammer phenomenon.

3.4 Hydraulic resistances

The authors have suggested a theoretical method to determine the hydraulic resistances for the simplest flow-branching and merging problems, and a method to control the hydraulic resistances until achieving the desired flow and heat transfer in two-phase flow case [3].

This method was appropriate for single-phase flow without phase change, but it was found that if phase change is present, such as a feedwater heater, it may cause code run failure in the process of controlling the hydraulic resistances at several points simultaneously. Thus, until a method with numerical stability is developed, it seems that this problem will eventually need iteration process adjusting in an empirical way, starting from the theoretically derived values.

3.5 Others

Frequently, detailed design data of the secondary system of a plant cannot be obtained for various reasons. In this case, data should be estimated from the available industry product models [10] or industrial standards [11, 12].

In general, many components of the secondary system are complexly connected, so significant calculation time is required to obtain a stable converged steady state. According to the authors' calculation experience, a minimum transient calculation of 1.5 hours is required.

4. Example of Modeling

A modeling of the secondary system was developed according to the modeling guidelines presented in the previous section. The target plant was SMART100 standard design [13]. However, little information about this plant was provided except for heat balance, so it was forced to refer to the available data of industrial product models. In this sense, this modeling is regarded as one of the general secondary system modeling that can satisfy the heat balance of the secondary system of the plant.

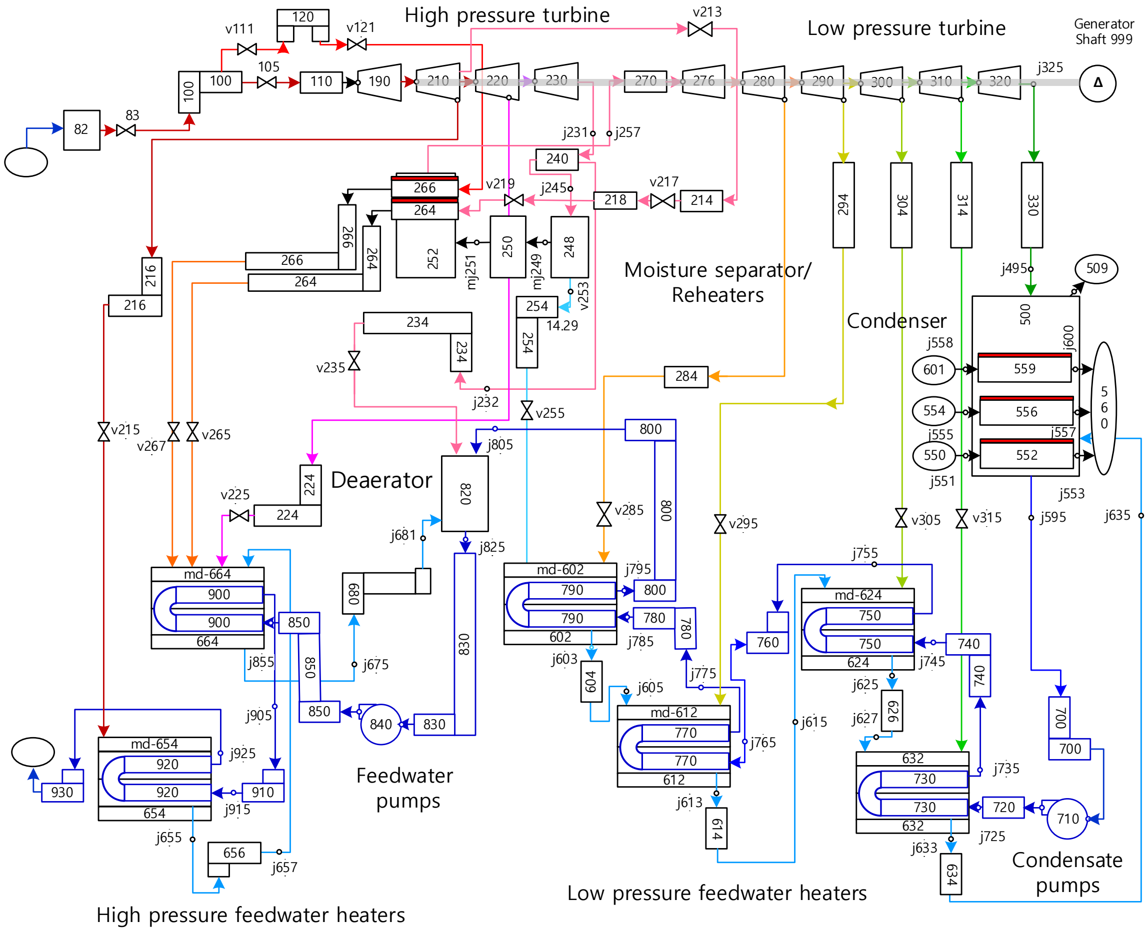

Fig. 1. MARS-KS modeling of secondary system

MARS-KS nodding diagram is shown in Fig.1. Three and five turbine components were modeled for HPT, and LPT, respectively. High pressure FWH and low pressure FWH were modeled by two and three MULTID components, respectively. And the model has two and three steam extractions from the HPT and LPT, respectively.

Fig.2 shows a pressure distribution from the inlet of HPT to the outlet of high pressure FWH. From this result, we can confirm overall performance from steam to feedwater was reasonably calculated.

Fig. 3 shows a comparison of pressure distribution of condensate water from the high pressure FWH (location 1) to the condenser return line (location 14). Although some differences in the two high-pressure FWH were found, pressure of low- pressure FWH were well agreed to the target data.

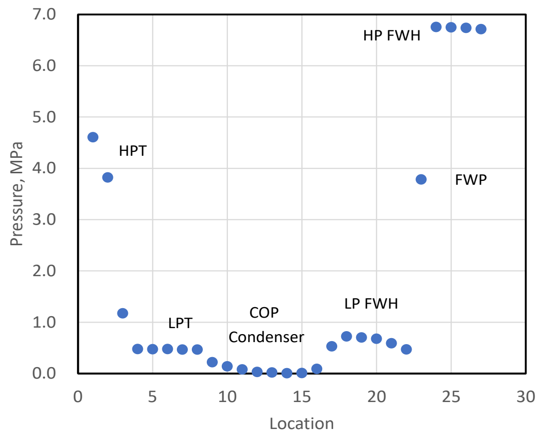

Fig. 2. Calculated pressure distribution

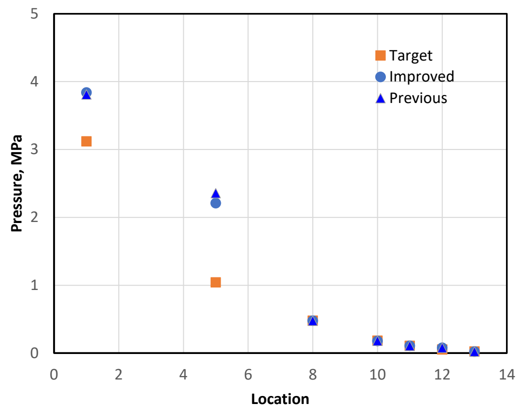

Fig. 3. Comparison of pressure of condensate water

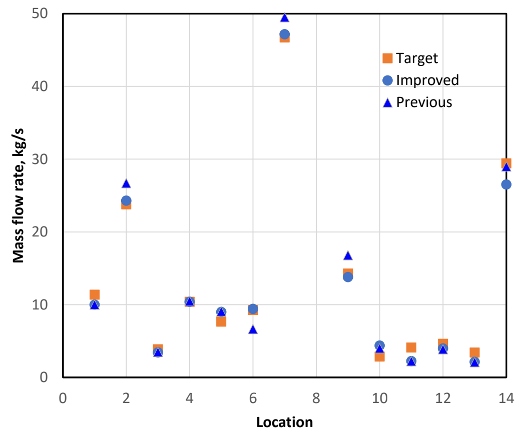

Fig. 4. Comparison of mass flow rates of condensate water

Fig. 4 show a comparison of mass flow rates of steam extracted from HPT (location 6 or less) and LPT (location 8 or higher) to FWH and Deaerator (location 7). As shown in the figure, all the flow rates are well agreed to the target values. In both figures, the 'Previous' means the result before fine tuning of hydraulic resistances. As shown in the figure, the fine tuning result shows that improvement is effective even at small flow rates.

5. Conclusions

The present paper discussed a guideline of the secondary system modeling in use of MARS-KS Code for NRHES. This guideline presents the details necessary for reasonable modeling obtained from the authors' modeling and computational experience. In addition, example modeling faithfully developed in this guidance and its calculations have shown that this guidance is reasonable. Although there are some parts for further improvement, at the current level, the use of this guidance is expected to save time and effort for secondary system modeling and thus the application of NRHES.

ACKNOWLEDGEMENT

This work is supported by the Nuclear Research & Development program in the form of a National Research Foundation (NRF) grant funded by the Korean government Ministry of Trade, Industry, and Energy (No. 2021M2D1A1084837).

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