Development of SMR Secondary side MARS-KS input for Artificial Intelligence Operational Scheme

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1. Introduction

In recent years, researches are being conducted to adapt AI (artificial Intelligence) into various functions in nuclear power plants. In KAIST, a preliminary research is underway in the ERC (Engineering Research Center) Project to operate a newly designed small modular nuclear power plant, namely ATOM, through artificial intelligence using reinforcement learning algorithms. To make well-trained AI operator, enough datasets from simulations are needed. Therefore, in the ERC project, ATOM MARS-KS input is being constructed in which the primary side and the secondary side are simulated at the same time in order to create coherent nuclear power plant operation datasets under various operational modes. Most of nuclear power plants safety analysis in the past do not simulate the secondary side in detail. However, to develop AI for nuclear power plant, it is necessary to model all of the primary and secondary systems, components and control logic.

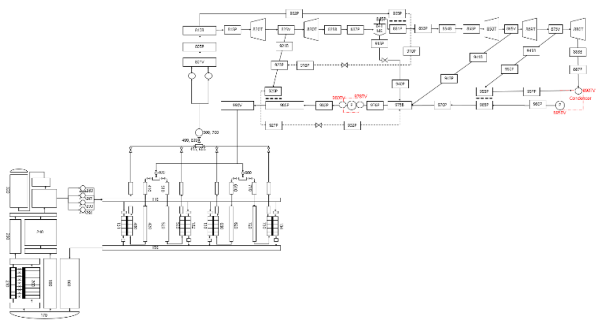

Fig. 1. ATOM nodalization of MARS-KS 1.4 simulation

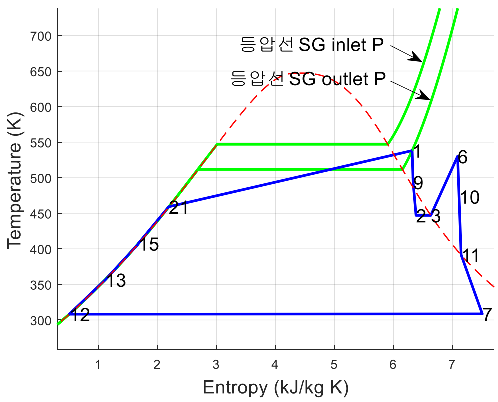

Fig. 2. Designed Rankine Cycle T-S diagram

The secondary side of ATOM was designed by KAIST RCD code developed in KAIST which is modified version of KAIST CCD code for designing a steam Rankine cycle. [4] In this study, ATOM MARS-KS input was made which has similar results compared with KAIST RCD code results. In addition, the original MARS-KS turbine model had some issues and has been modified correctly to calculate accurate results. The module is updated to utilize a steam turbine map for calculating turbine efficiency in transient simulation.

2. Modified Turbine model

2.1. Steam turbine map

In order to control the steam turbine in safety analysis code, it is necessary to simulate the turbine having different efficiency according to the given inlet and outlet conditions. Therefore, a virtual turbine map was created by using Stodola's cone law and aerodynamic scaling.

By stodola's cone law, expansion ratio of turbine can be predicted when Pin, Tin is fixed.

$$\frac{m}{m_d}=\frac{\frac{P_{in}}{\sqrt{T_{in}}}}{\frac{P_{in,d}}{\sqrt{T_{in,d}}}}\sqrt{\frac{1-\left(\frac{P_{out}}{P_{in}}\right)^{\frac{n+1}{n}}}{1-\left(\frac{P_{out,d}}{P_{in,d}}\right)^{\frac{n+1}{n}}}}\cong\sqrt{\frac{1-(P_{out}/P_{in})^{\frac{n+1}{n}}}{1-(P_{out,d}/P_{in,d})^{\frac{n+1}{n}}}}\cong\sqrt{\frac{1-(P_{out}/P_{in})^{2}}{1-(P_{out,d}/P_{in,d})^{2}}}$$

The efficiency according to the change in enthalpy is shown as follows.

$$\eta=\eta_d-\alpha\left[\frac{\frac{N}{\sqrt{\Delta H}}}{\frac{N_d}{\sqrt{\Delta H_d}}}-1\right]^2\cong\eta-\alpha\left[\frac{\sqrt{\Delta H_d}}{\sqrt{\Delta H}}-1\right]^2$$

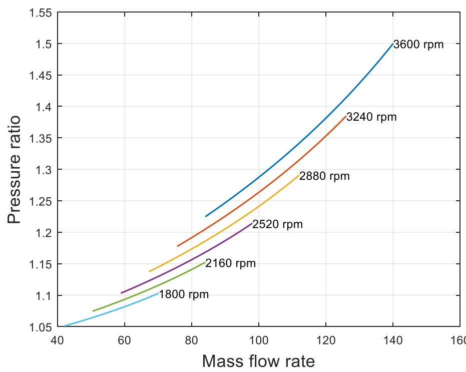

Fig. 3. Example of generated HP Turbine Map (Mass flow rate / Pressure ratio)

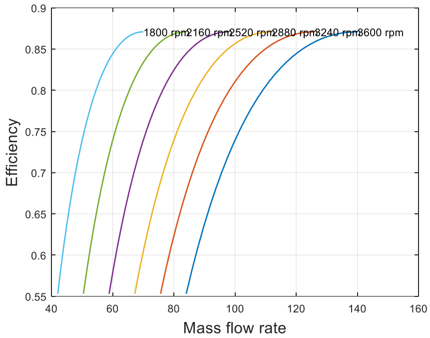

Fig. 4. Example of generated HP Turbine Map (Mass flow rate / Turbine Efficiency)

2.2. Turbine modeling

In original MARS-KS, turbine work is calculated as follows.

$$W = -\eta \int dh$$

$$= -\eta \int \frac{1}{\rho} dP \quad = -\eta \ \frac{1}{\rho} (P_{out} - P_{in})$$

However, for compressible flow in a turbine, the density of fluid (water, steam) is not constant as it passes through the turbine. Therefore, there is an error in the derived formula used in the calculation. Thus, MARS-KS turbine model was modified to calculated the accurate turbine exit condition. The modified turbine model uses a pre-generated turbine map and CEA model to calculate turbine outlet temperature, pressure and mass flow rate according to the given turbine inlet condition. The simulated results of the ATOM high pressure turbine are as follows.

Table. 1. Example of modified MARS-KS turbine result

	Design value	Modified MARS-Ks result	Error(%)
Inlet P [MPa]	3.2675	3.2628	0.14
Inlet T [K]	538.09	537.87	0.04
Inlet h [kJ/kg]	2888.159	2886.35	0.09
η	0.9041	0.9041	0.00
Outlet P [MPa]	2.1752	2.1752	0.00
Outlet T [K]	493.56	493.33	0.05
Outlet h [kJ/kg]	2812.31	2808.90	0.12
Mass flowrate [kg/s]	140.0417	140.04	0.00
Turbine work [MW]	10.7622	10.8453	0.77

It is confirmed that turbomachine performance result in KAIST RCD and MARS-KS turbine simulation result had only below 1% error.

3. MARS-KS Result

Modified turbine model is used to make the ATOM MARS-KS secondary side input. The biggest difference between KAIST-RCD and MARS-KS, is how pressure and mass flow are adjusted. In KAIST RCD, the pressure drop of a pipe or single volume is almost ignored, and the cycle calculation is based on the performance of the turbomachine. However, it is difficult to match the pressure to the design point in MARS-KS, since there is pressure drop in each pipe or single volume before entering the turbomachine. Therefore, in this study, in order to make the input that meets the design pressure and mass flow rate, the branching points in cycles were separated and treated as time dependent volumes, connected to single junctions for finding pipe area which makes design value. After that, time dependent volumes were removed by combining the separate inputs. In addition, where the design value differs significantly in the combined input, the flow loss coefficient of pipe is adjusted to converge the MARS-KS code result to the design value. The simulated results of the ATOM MARS-KS secondary side are as follows.

Table. 2. ATOM MARS-KS secondary side result

			Design conditions	MARS code results	Difference [%]
Cycle efficiency [%]			30.9027	35.4397	14.68
Turbine power [MW]			103.14	118.451	14.84
High pressure turbine	Inlet_1	P [MPa]	3.2675	3.0601	6.347
		T[K]	538.086	510.58	5.111
		$\dot{m}$ [kg/s]	140.0417	139.15	0.6367
	Inlet_2	P [MPa]	2.1752	1.99813	8.140
		T[K]	493.700	485.13	1.735
		$\dot{m}$ [kg/s]	130.2388	131.03	0.6074
	Outlet	P [MPa]	0.8701	0.79744	8.350
		T[K]	447.068	443.3	0.8428
		$\dot{m}$ [kg/s]	130.2388	131.03	0.6074
Low pressure turbine	Inlet_1	P [MPa]	0.7701	0.796777	3.464
		T[K]	530.146	470.94	11.16
		$\dot{m}$ [kg/s]	123.0793	125.42	1.901
	Inlet_2	P [MPa]	0.4530	0.466009	2.871
		T[K]	473.411	422.15	10.82
		$\dot{m}$ [kg/s]	113.2449	121.91	7.651
	Inlet_3	P [MPa]	0.1888	0.186191	1.381
		T[K]	391.662	390.69	0.2481
		$\dot{m}$ [kg/s]	104.6221	87.993	15.89
	Outlet	P [MPa]	0.0058	0.005869	1.189
		T[K]	308.567	308.86	0.09495
		$\dot{m}$ [kg/s]	104.6221	88.018	15.87

It is confirmed that the error difference is larger in the low pressure turbine than in the high pressure turbine. This is because the branch flow rate fits well with the design value in the high pressure turbine, while the branch flow rate differs from the design value in the low pressure turbine. Since the pressure drop does not occur significantly in the heat exchanger connected to the last branch of the low pressure turbine, it is difficult to accurately set the branch flow rate.

4. Conclusions

As a result of the study, it was possible to make SMR (ATOM) secondary side input with MARS-KS code. It is confirmed that the temperature, pressure and mass flowrate of each pipe and volumes were not significantly different compared with the cycle optimization code KAIST RCD. In part, the difference was as large as 15%, presumably due to the influence of the heat exchanger model. In the power system cycle, there is a process of preheating and reheating for improving cycle efficiency. Since there is no suitable heat exchanger component that can be used for preheating and reheating in MARS-KS code, the heat exchanger was replaced with a heat structure model in MARS-KS. In the future, the heat exchanger model for the power system will be improved, and power cycle will be controlled by replacing the loss junction with a motor valve.

Acknowledgement

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REFERENCES

[1] MARS CODE MANUAL VOLUME I: Code Structure, System Models, and Solution Methods, KAERI
[2] MARS CODE MANUAL VOLUME II: Input Requirements, KAERI
[3] MARS CODE MANUAL VOLUME III: PROGRAMMER’S MANUAL
[3] MARS CODE MANUAL VOLUME V: Models and correlations, KAERI
[4] M.S. Kim, Study on the supercritical CO2 power cycles for landfill gas firing gas turbine bottoming cycle, Energy, pp.893-909, 2016