Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 23-24, 2019

Preliminary study on modified steam turbine modeling of the MARS-KS code

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1. Introduction

In recent years, renewable energy such as solar energy with high intermittency has been expanding in the electricity market. Therefore, it is anticipated that nuclear power plants, which operate as the base load, will require the load following capability to match the intermittency of the renewable energy. In KAIST, a preliminary research is under way in ERC (Engineering Research Center) project to operate a newly designed small modular nuclear power plant, namely ATOM, through an artificial intelligence using reinforcement learning algorithms for load following operation.

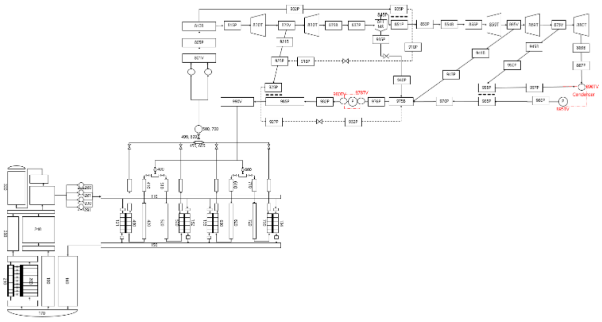

Fig. 1. ATOM nodalization of MARS-KS 1.4 simulation

To construct a well-trained AI operator, enough datasets 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.

The secondary side of ATOM was designed by KAIST RCD code developed in KAIST which can design a Rankine cycle. It is confirmed that there is a difference between the MARS-KS ATOM simulation results and the design values of KAIST RCD. As a result of analysis of the difference, it is confirmed that power output and outlet condition of a turbine are inaccurate due to the assumption used in the MARS-KS turbine module. In this paper, MARS-KS turbine module is modified to calculate the power output and outlet condition accurately for given inlet pressure, outlet pressure, and turbine efficiency.

2. Methods

2.1 Original MARS-KS Turbine model

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

$$\frac{1}{2}v_{in}^2 + h_{in} = \frac{1}{2}v_{out}^2 + h_{out} + W_{turb}$$

W_{turb} represents the shaft work per mass flow rate extracted from the fluid in the turbine.

In the idealized process where external heat loss and internal dissipation are neglected, the process is isentropic and $dh = \frac{1}{\rho}dP$.

Integrating the above equation from the inlet to the outlet gives $h_{out} - h_{in} = \frac{1}{\rho}(P_{out} - P_{in})$.

The actual work per mass flow rate, W, produced by the fluid on the rotating blades as its momentum is changed, is usually written as an efficiency times the isentropic enthalpy changes across the stage and becomes

$$\begin{aligned} W &= -\eta \int dh \\ &= -\eta \int \frac{1}{\rho}dP = -\eta \frac{1}{\rho}(P_{out} - P_{in}) . \end{aligned}$$

However, for compressible flow in a turbine, the density of fluid(water) is not constant as it passes through the turbine. Therefore, there is an error in the derived formula used in the calculation.

In order to observe the error of the MARS-KS turbine model, the error was obtained for the simulation of MARS-KS was performed with the inlet condition of the ATOM high pressure turbine.

Table. 1. Inlet and Outlet condition of MARS-KS turbine simulation test case

Steady state	Temperature[K]	Pressure[Pa]	Mass flowrate [kg/s]
Inlet	608.38	3.07810E+06	14.243
Outlet	537.50	1.59282E+06	

Table. 2. MARS-KS turbine simulation data and error

	Equation	Value
MARS-KS turbine power [W]	$\dot{m}(-\eta \frac{1}{\rho}(P_{out} - P_{in}))$ $\eta = 0.9$	2.060E+06

Turbine power true value [W]	$\dot{m}(\frac{1}{2}{v_{out}}^2 + h_{out} - \frac{1}{2}{v_{in}}^2 + h_{in})$	1.807E+06
Error	13.96%	

In addition, in MARS-KS, the outlet condition of the turbine is not the same as the design value. The energy extracted from the turbine should be calculated from the internal energy equation of volume as heat, which is calculated from the momentum equation in the code.

2.2 Modified MARS-KS Turbine model

It is not practical to accurately simulate phenomena occurring in the turbine with the 1-D code. However, from the fact that the effect of the turbine is to extract energy from a fluid flow, the turbine can be simplified in the 1-D code as a heat exchanger and a throttling valve. In the modified MARS-KS turbine model, the calculated turbine work is subtracted from the inlet flow volume internal energy, and the turbine junction is used as a throttling valve to reduce the pressure while maintaining enthalpy.

Therefore, MARS-KS turbine model is modified as shown in the following flowchart. In the process of calculating entropy, since there is no entropy data in the water property files, tpfh2o and tpfh2onew, used in MARS-KS, NIST's refprop water entropy data is directly called from the MARS-KS source code.

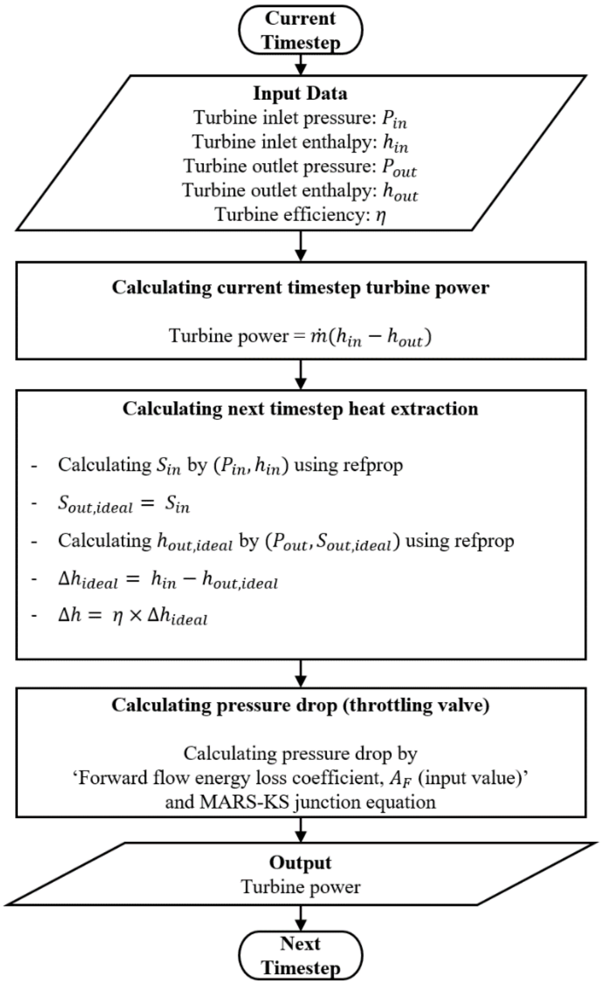

Fig. 2. Flow chart of modified MARS-KS turbine model

In the above test case, when the turbine power true value is calculated, the term due to the velocity difference is 0.0045% of the term due to enthalpy difference. In the actual turbine, the fluid velocity difference of the turbine inlet and outlet is negligible when calculating turbine power because it is much smaller than the enthalpy difference, so the term due to the velocity difference is ignored in the modified model.

In the original turbine model, pressure drop is calculated from the momentum equation. In the modified turbine model, pressure drop is determined by the 'Forward flow energy loss coefficient' of the turbine outlet junction and MARS-KS junction equation. Therefore, to adjust the turbine outlet pressure to another value, user should change the junction loss coefficient value in the input file.

The efficiency of the turbine should be calculated from the turbine map through the pressure ratio and the corrected mass flowrate. However, in this study, the authors assumed a constant efficiency turbine to see if the modified turbine model accurately calculates turbine power and outlet conditions.

3. Results

3.1 Test case

Table. 3. Inlet and Outlet condition of MARS-KS turbine simulation test case

	Temperature [K]	Pressure [Pa]	Mass flowrate [kg/s]	Efficiency
Inlet	608.33	3.07684E+06	45.054	0.9
Outlet	529.77	1.59127E+06		

Table. 4. MARS-KS modified turbine model test case simulation result

Inlet Enthalpy [J/kg] h_{in}	3.08026E+06
Outlet Enthalpy [J/kg] h_{out}	2.93518E+06
Outlet ideal Enthalpy [J/kg] $h_{out,ideal}$ (Isentropic process)	2.91906E+06
Turbine Power [W]	6.53614E+06

Table. 5. Simulation entropy result error

Pressure [Pa]	Enthalpy [J/kg]	Entropy [J/K·kg]	Error (entropy)
3.07684E+06	3.08026E+06	6.6758E+03	0.0042%
1.59127E+06	2.93518E+06 (Isentropic process)	6.6761E+03	

Table. 6. Simulation enthalpy result

Outlet Enthalpy [J/kg]	2.93518E+06
$h_{in} - (h_{in} - h_{out,ideal}) \times \eta$ [J/kg]	2.93518E+06

It is confirmed that the isentropic turbine work is accurately calculated in the modified turbine model. In addition, it is confirmed that the power output of the turbine is the same as $'\text{Isentropic turbine work}' \times' \text{turbine efficiency}'$.

3.2 Changing turbine junction loss coefficient

- Forward flow energy loss coefficient: 1000 (test case)
Inlet pressure[Pa]: 3.07684E+06
Outlet pressure[Pa]: 1.59127E+06
Mass flowrate [kg/s]: 45.054
Turbine power [W]: 6.53614E+06

- Forward flow energy loss coefficient: 100
Inlet pressure[Pa]: 3.06440E+06
Outlet pressure[Pa]: 1.57583E+06
Mass flowrate [kg/s]: 141.97
Turbine power [W]: 2.05712E+07

- Forward flow energy loss coefficient: 10
Inlet pressure[Pa]: 2.95175E+06
Outlet pressure[Pa]: 1.53179E+06
Mass flowrate [kg/s]: 432.14
Turbine power [W]: 6.16236E+07

- Forward flow energy loss coefficient: 1
Inlet pressure[Pa]: 2.66002E+06
Outlet pressure[Pa]: 1.99503E+06
Mass flowrate [kg/s]: 801.89
Turbine power [W]: 4.34339E+07

Pressure ratio, mass flowrate, and turbine power are changed by changing the turbine junction loss coefficient between the same time-dependent volumes. As the loss coefficient increases, the pressure ratio increases and mass flowrate decreases.

4. Conclusions

As a result of the study, it was possible to modify the turbine model for preparing the secondary side input of MARS-KS code. In the modified turbine model, turbine power is obtained accurately by using the prescribed efficiency, inlet and outlet pressures. In the future, the turbine efficiency model will be improved via using turbine map, and in the transient simulation, additional modification will be added to change the outlet pressure of the turbine to the desired value.

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