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Comparison of steam turbine modelling methods for SMART100 Secondary System analysis

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1. Introduction

Within a life cycle of a Nuclear Power Plant (NPP) there are numerous occasions when there is a need of off-design secondary cycle behavior detailed analysis, including cycle optimization, degraded heaters performance, steady-state parameters for transient analysis or evaluation of an impact of a cycle modification. Commonly, these evaluations are performed using heat-and-mass-balance codes (e.g., PEPSE). The essential aspect for such calculations is to accurately determine turbine performance, especially variation of turbine extraction pressures which is highly nonlinear for multistage turbines with un-chocked flow. [1]

In the area of nuclear Rankine cycle modeling, previous investigations have focused mostly on modeling methods applied to large, commercial NPPs. Steam turbine modeling for light water Small Modular Reactor (SMRs) is not sufficiently addressed in the literature.

This study aims to compare different turbine modeling methods applied to System-integrated Modular Advanced Reactor (SMART100) turbine. For this purpose, three SMART100 secondary cycle computational models are developed applying different approaches. The models are simulated using OpenModelica (OM) and the simulation results are compared to SMART100 data provided in the Standard Safety Analysis Report (SSAR) [2].

2. SMART100 Secondary System

The SMART100 is provided a standard Rankine cycle with one High Pressure Turbine (HPT) and one Low Pressure Turbine (LPT). The HPT is supplied with Main Steam (MS) from Once-Through Steam Generators (OTSGs). It should be noted that the OTSGs produce slightly superheated steam and that the steam expansion occurs in uncontrolled manner to high vacuum. A two-stage Moisture Separator Reheater (MSR) dries and superheats the cross-around steam. The 1st stage of the steam reheat is supplied with extraction steam and portion of MS is extracted to the 2nd stage of steam reheat. Extraction steam is also supplied to a heat regeneration system with seven points of heating (four low pressure Feedwater Heaters (FWHs), deaerator, and two high pressure FWHs). The SMART100 turbine generator is a 3600 rpm unit with the generator power output around 120 MW_e.

3. Methodology

3.1. Turbine Modeling Methods

First of the turbine modeling method investigated in this paper is a deductive approach formulated by A. Ray based on approximation of fundamental equations [3]. The turbine performance is calculated as follows

$$\frac{\dot{m}}{\dot{m}_{ref}} = \sqrt{\frac{p_{in}{}^{\mu} - p_{out}{}^{\mu}}{p_{in,ref}{}^{\mu} - p_{out,ref}{}^{\mu}}} \tag{1}$$

$$\mu = \frac{\kappa(2-\eta)+\eta}{\kappa} \tag{2}$$

$$\kappa = \frac{c_p}{c_v} \tag{3}$$

where, $\dot{m}$ – steam mass flow rate through a turbine stage group, $\dot{m}_{ref}$ – steam mass flow rate through a turbine stage group at reference condition, $p_{in/out}$ – steam pressure at the inlet/outlet of a turbine stage group, $p_{in/out,ref}$ – steam pressure at the inlet/outlet of a turbine stage groups at reference condition, μ - exponent factor, κ – adiabatic index, η – turbine stage group thermodynamic efficiency, c_p – isobaric specific heat capacity, and c_v – isochoric specific heat capacity. Application of this method to a standard Pressurized Water Reactor (PWR) Rankine cycle is demonstrated in a referred publication [4]. This approach is referred in this study as method 1.

The alternative approach is proposed by A. Stodola and it is commonly known as the ellipse law. [5] This method has been derived empirically and it is the most popular model for steam turbine performance calculation. One interpretation of the ellipse law applied to model the AP1000 turbine is expressed as follow [6]

$$\frac{\dot{m}}{\dot{m}_{ref}} = \sqrt{\frac{p_{in}{}^{2} - p_{out}{}^{2}}{p_{in,ref}{}^{2} - p_{out,ref}{}^{2}}} \tag{4}$$

This modeling approach is referred in this paper as method 2.

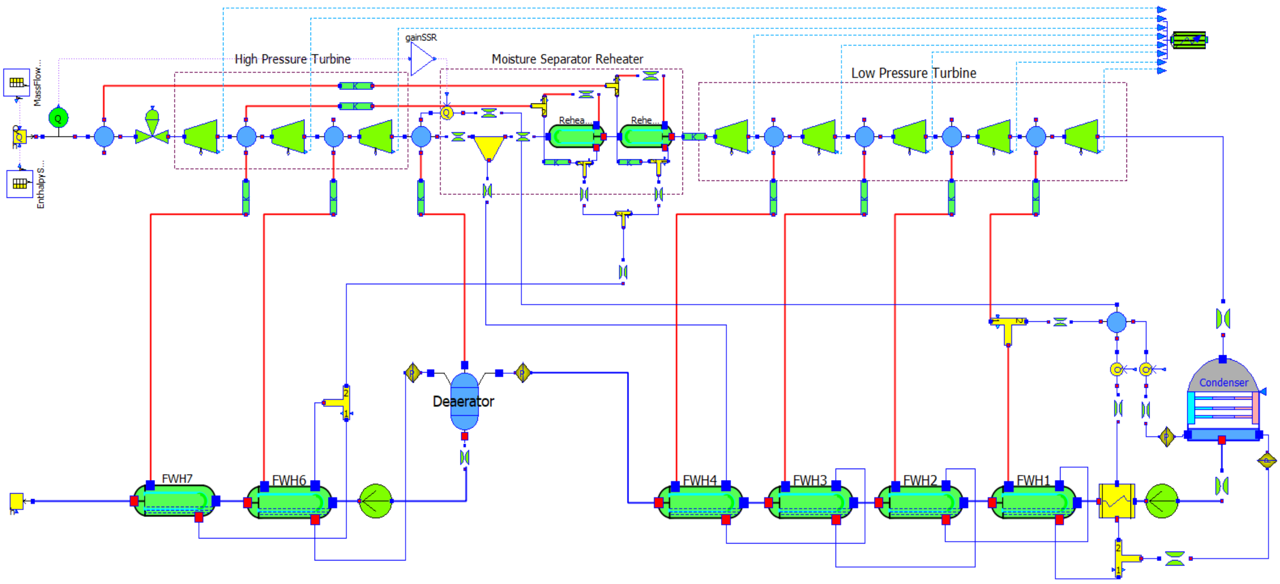

Fig.1. SMART100 secondary system model developed in OpenModelica

The last approach considered in this research (hereafter referred to as method 3) is another interpretation of the Stodola's formulation, where additionally effects of steam temperature and steam quality are taken into consideration. [7]

$$\frac{\dot{m}}{\dot{m}_{ref}} = \sqrt{\frac{{p_{in}}^2 - {p_{out}}^2}{{p_{in,ref}}^2 - {p_{out,ref}}^2}} \sqrt{\frac{T_{in,ref} \cdot x_{in,ref}}{T_{in} \cdot x_{in}}} \quad (5)$$

where, T_{in} – inlet steam temperature, x_{in} – vapor mass fraction at the inlet, $T_{in,\ ref}$ – inlet steam temperature at reference condition, and $x_{in,ref}$ – inlet vapor mass fraction at the inlet at reference condition. This approach is used in a general steam turbine model of the ThermoSysPro (TSP) OM library developed by the Électricité de France (EDF). This OM library has been validated for application to model a secondary cycle of an NPP [8].

For all the methods the reference condition is the Valves Wide Open (VWO) condition (equivalent of 5% overpressure condition) as it is a common practice in the industry. Furthermore, in case of all of the turbine models the stage group thermodynamic efficiency is calculated according to the following equation

$$\eta = \frac{h_{in} - h_{out}}{h_{in} - h_{out,s}} \quad (6)$$

where, $h_{in/out}$ – steam specific enthalpy at the inlet/outlet of a turbine stage group, $h_{out,s}$ – steam isentropic specific enthalpy at the outlet of a turbine stage group.

3.2. SMART100 Secondary Cycle Model Development

OpenModelica is used as modeling and simulation software for this study (OM version 1.18.0). The previous work provided evidence that OM is a reliable tool for quasi-steady state heat-and-mass-balance calculation for nuclear Rankine cycle. [9]

In this work three SMART100 secondary cycle quasi-steady state models are developed based on the design data provided in the SMART100 SSAR [2]. Each of the OM models applies different turbine modeling method (see Section 3.1.). Moreover, the major Rankine cycle components are calculated based on the first law of thermodynamics (Eq.7) and the mass balance equation (Eq.8).

$$\frac{dE}{dt} = \dot{Q} - \dot{W}_{sys} + \sum_{i=1}^{IN} \dot{m}_i \left[h_i + \frac{v_i^2}{2} + gz_i \right] - \sum_{j=1}^{OUT} \dot{m}_j \left[h_j + \frac{v_j^2}{2} + gz_j \right] \quad (7)$$

$$\frac{dM}{dt} = \sum_{i=1}^{IN} \dot{m}_i - \sum_{j=1}^{OUT} \dot{m}_j \quad (8)$$

where, E – energy of a system, Q – heat energy transferred into the system, $\dot{W}_{sys}$ – work energy performed by a system, $\dot{m}_{i/j}$ – fluid mass flow rate at the inlet/outlet of a system, $h_{i/j}$ – fluid specific enthalpy at the inlet/outlet of a system, $v_{i/j}$ – velocity of the fluid at the inlet/outlet of a system, g – gravitational constant, $z_{i/j}$ – elevation of the fluid at the inlet/outlet of a system, IN/OUT – total number of inlets/outlets of a system, M – mass of the medium. The OTSG modelling is excluded from the scope of this evaluation.

The models are simulated at VWO and Maximum Guaranteed Rate (MGR) conditions. It should be noted that MGR is equivalent to a nominal power level.

Subsequently, the simulations results are compared to the SMART100 reference data [2] (see section 4).

One of the developed SMART100 secondary cycle OM models is presented in Fig.1.

4. Results and analysis

The secondary system simulation results accuracy is indicated by relative error calculated between the simulation results of a given model and the SMART100 reference data. This parameter was calculated for mass flow rates and pressures at representative points in the cycle at VWO and MGR conditions. The mass flow rates values were collected at 51 points across the Rankine cycle and the pressure levels were collected at 31 points of the system. These accuracy indicators for all the analyzed models are illustrated in Figs. 2 and 3.

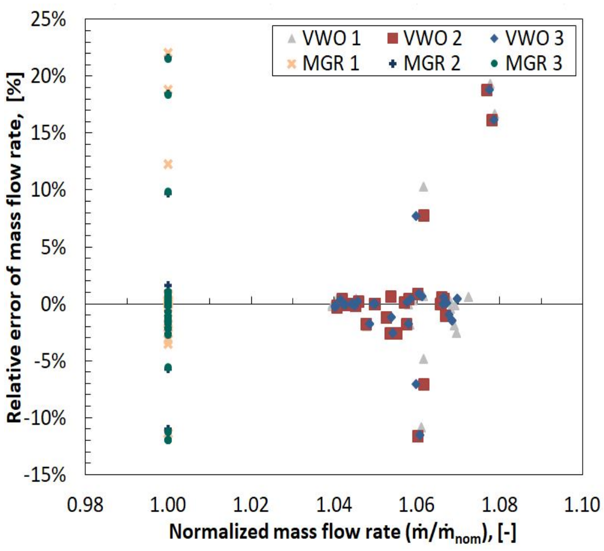

Fig.2. Relative error of mass flow rate plotted against normalized mass flow rate.
(Note that the numbers indicated in the legend correspond to the method number)

Fig.2. shows the relative error of mass flow rate plotted against a normalized mass flow rate. From Fig.2 can be observed that the three turbine modeling methods provide very similar results. In case of method 1 88% of data points falls into a relative error range of ±5%, while for methods 2 and 3 86% of data points can be found within these limits. The largest values of relative error reach approximately 22%. Such departure from expected values is caused by limitations in availability of the input data for the models. Due to lack of sufficient data some phenomena that could affect the accuracy of simulation results (e.g., gland steam leakages to extraction steam lines) are not in the scope of this study.

The relative error of pressure in a function of a normalized steam pressure is presented in Fig.3. These results are in line with the findings of Fig.2, indicating similarity in the simulation accuracy for all three models. Considering the relative error range of ±5%, for method 1 95% of pressure values falls into this region and in case of methods 2 and 3 97% of the data points can be found within this range. From the analysis of Figs. 2 and 3, it is evident that the methods 2 and 3 produce nearly identical results.

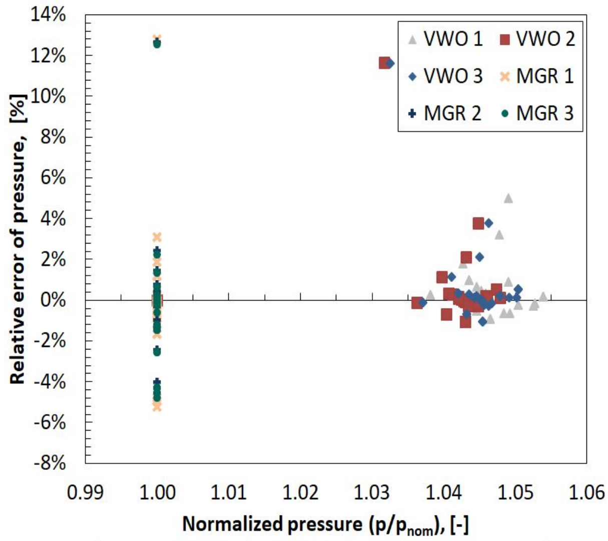

Fig.3. Relative error of pressure plotted against normalized pressure.
(Note that the numbers indicated in the legend correspond to the method number)

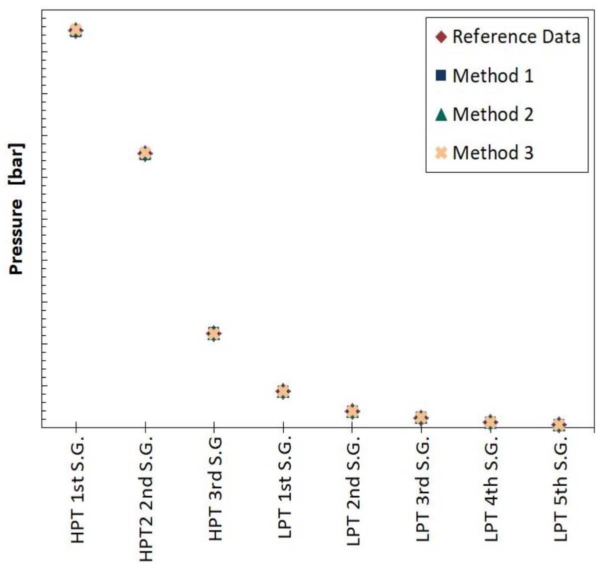

Fig.4. Inlet steam pressure for SMART100 HPT and LPT Stage Groups (S.G.) at VWO condition

The inlet steam pressure for each of the HPT and LPT stage groups at VWO and MGR conditions is illustrated in Figs. 4 and 5. These diagrams demonstrate that all the analyzed methods accurately model the SMART100 turbine performance. From these figures can be seen that the pressure values across the steam flow path are essentially the same as indicated at the SMART100 heat balance diagrams in the SSAR [2]. The absolute values of the relative error between the simulation results and the reference data are below 1% at VWO condition (see Fig.4) and below 2.6% at MGR condition (see Fig.5).

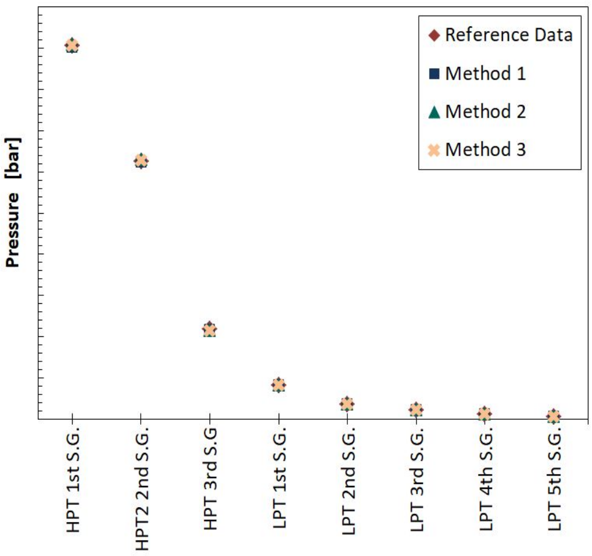

Fig.5. Inlet steam pressure for SMART100 HPT and LPT Stage Groups (S.G.) at MGR condition

5. Conclusions

The SMART100 secondary cycle quasi-steady state models are developed using OpenModelica modeling and simulation software. The models apply three different methods for steam turbine modeling in order to compare the alternative approaches for application in light water SMR Rankine cycle analysis. Although the results indicate a need for more detailed data input to improve the accuracy of the simulation results, all the analyzed methods has proven its adequacy for the SMART100 turbine modeling. This study demonstrated that the difference in simulation results between the three models is minimal.

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