*Transactions of the Korean Nuclear Society Virtual Autumn Meeting*
*October 21-22, 2021*

# APR1400 Secondary Cycle Modeling Integrated with Thermal Energy Storage Using OpenModelica

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## 1. Introduction

Over the past decade, mitigation of the climate crisis became the main goal while shaping energy policies. Following the Paris agreement, many countries pledged to become carbon neutral until 2050. Important role of nuclear energy in this strict energy transition plan has been recognized by one of the leading authoritative analysis provider, International Energy Agency (IEA). IEA considers that nuclear energy contribution is essential to reach ambitious climate goals in a timely and cost-efficient manner [1].

The future energy sector is expected to be highly penetrated by non-dispatchable and variable renewable energy sources. Thus, Nuclear Power Plants (NPPs) are required to adapt to aforementioned energy systems where dispatchable energy sources provide flexible power output to assure secure electricity supply.

Historically, NPPs has been designed to operate as baseload units with high capacity factor. Flexible operation penalizes NPP operators with increased maintenance cost, technical issues and challenged economic viability. One proposed solution to enhance flexible NPP operation and concurrently to avoid the adverse consequences is to operate continuously at full reactor rated power level while the power load of the secondary cycle would vary to match grid demand through integration with a tertiary cycle that would either store or use the exported heat. There are various ways to utilize the heat extracted from a nuclear steam cycle such as Thermal Energy Storage (TES), water desalination, hydrogen production, oil refining etc. Design and optimization of the NPP integrated with an external heat utilization facility require employment of appropriate simulation methods that are suitable for multiphysics modeling.

This research presents development of the APR1400 secondary cycle model using OpenModelica (OM). Furthermore, this work focuses on validation of nuclear Rankine cycle OM model integrated with TES against PEPSE simulation results presented in the literature [2].

## 2. APR1400 integrated with TES

The APR1400 secondary cycle is illustrated at Fig.1. The APR1400 is provided with a standard modern nuclear Rankine cycle with one High Pressure Turbine (HPT) and three Low Pressure Turbines (LPTs). Two-stage Moisture Separator Reheaters (MSRs) dry and superheat cross-around steam. Extraction Steam (ES) is supplied to heat regeneration system with seven points of heating (three low pressure Feedwater Heaters (FWHs), deaerator, and three high pressure FWHs) and to 1st stage of steam reheat. Portion of Main Steam (MS)

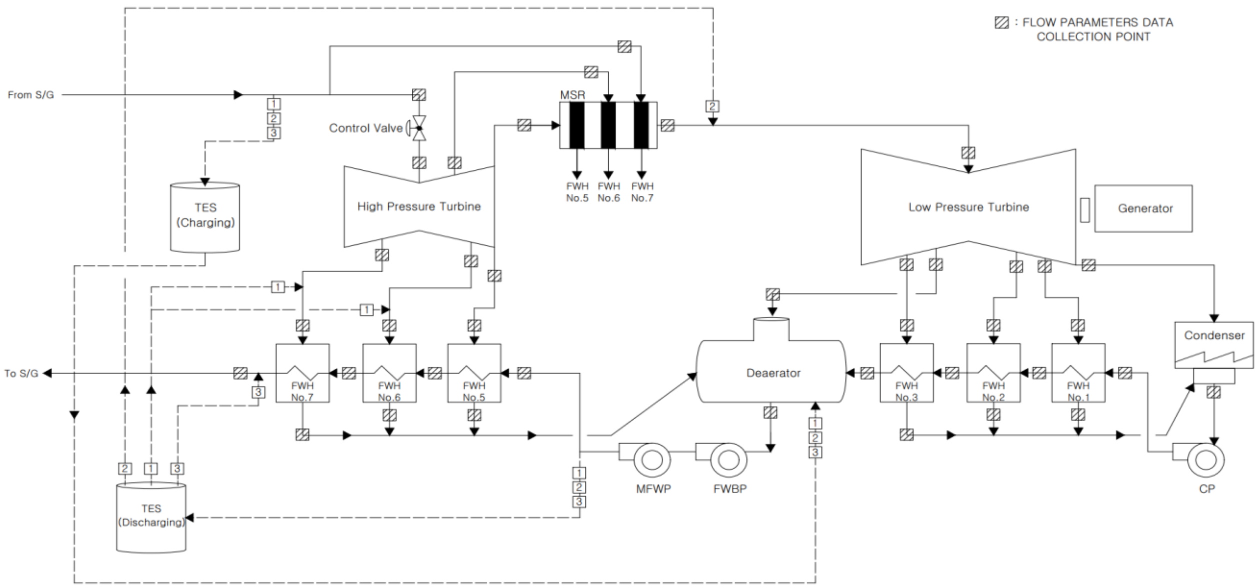


Fig.1. Simplified diagram of the APR1400 secondary cycle integrated with three different configurations of TES interface (numbered 1, 2, and 3) for storage charging and discharge operation (dashed lines indicate the TES interface pipelines).

supplied by Steam Generators (S/Gs) is extracted to 2nd stage of cross-around steam reheat. The APR1400 net generator power output is 1400 $MW_e$.

For the purpose of this research APR1400 secondary cycle is integrated with three alternative TES interface configurations described in a reference paper [2]. These TES arrangements are indicated in Fig.1. The coupled systems operation in a diurnal cycle assumes storage charging with 20% of rated Nuclear Steam Supply System (NSSS) power equivalent to 800 $MW_{th}$ for 8 hours. The stored heat is then recovered at lower rate, approximately 11% of NSSS power (450 $MW_{th}$). Thus, the duration of storage discharge operation in a 24h cycle would be close to double of the storage charging period. The description of the TES interface configurations and details on constrains that determine system operation are provided in the referred work [2].

## 3. Methodology

### *3.1.OpenModelica*

Modelica is an equation based, object oriented, non-proprietary language developed to model complex physical systems containing e.g., mechanical, electrical, hydraulic, thermal, control or process-oriented subcomponents. The design and optimization process of a system that would integrate a NPP and an external heat utilization facility is expected to require multiphysics modeling. Therefore, Modelica is proposed as a modeling language for the investigation presented in this paper.

OM is an open-source Modelica modeling and simulation environment. This free of charge software allows interactive execution of most of the Modelica expressions, algorithms, and functions. OM compiles the equation based models into C code which is linked with a library of utility functions, a run-time library, and a numerical Differential and Algebraic Equation (DAE) solver. OM provides also advanced graphical user interface, OMEdit, to facilitate complex model development. [3] The models presented in this research were developed in OM version 1.17.0.

In this work a customized library is developed based on the Modelica Standard Library (MSL) version 3.2.3. and ThermoSysPro (TSP) library version 3.2 developed by the Électricité de France (EDF).

### *3.2. Model development*

The model development methodology is presented in Fig.2. The APR1400 secondary cycle baseline OM model (Fig. 3.) is developed based on the design data provided in the public record [4]. The accuracy of the baseline simulation is then assured comparing the simulation results to the APR1400 heat balance diagrams at four different power levels: Valves Wide Open (VWO), Maximum Guaranteed Rate (MGR), 75% of nominal power, and 50% of nominal power. Note that MGR condition corresponds to the rated power level and VWO is equivalent to 104% of APR1400 nominal power. In order to compare the data 42 representative points in the cycle are selected (see Fig.1.) to collect the key flow parameters: mass flow rates, pressures, and enthalpies. Furthermore, turbine stage groups shaft power and generator power output are considered as indicators of the turbine-generator performance. This data set is used to quantify the relative error between the simulation results and the design data [4].

Subsequently, the validated model serves as a base for further investigations. The baseline model is modified to reflect three different TES interface arrangement configurations illustrated in Fig. 1. The simulation is performed under storage charging and discharging operating conditions. The resulting performance data is compared with simulation results published elsewhere [2]. The referenced research used commercial software PEPSE™ to investigate thermodynamic performance of APR1400 secondary cycle integrated with Nuclear Heat Storage and Recovery (NHSR) System.

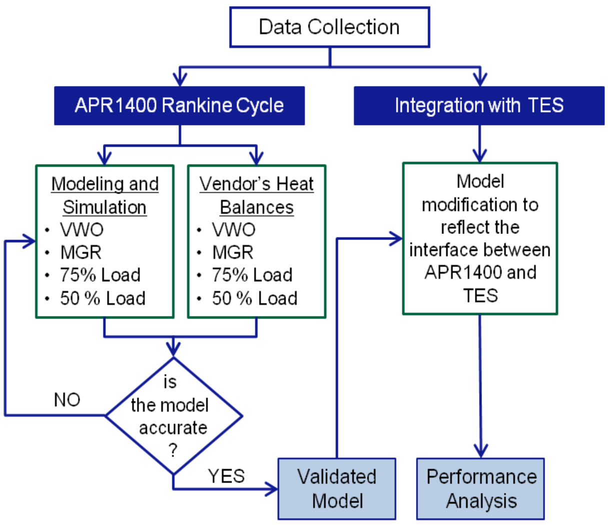


Fig.2. Model development methodology flow diagram

The scope of this research is limited to development of a simplified quasi-steady state heat balance model of the analyzed system. The main Rankine cycle components are modeled as separate objects that are connected into simplified APR1400 secondary system as presented in Fig.3. The sub-models are quantified based on the first law of thermodynamics for an open system (Eq.1).

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

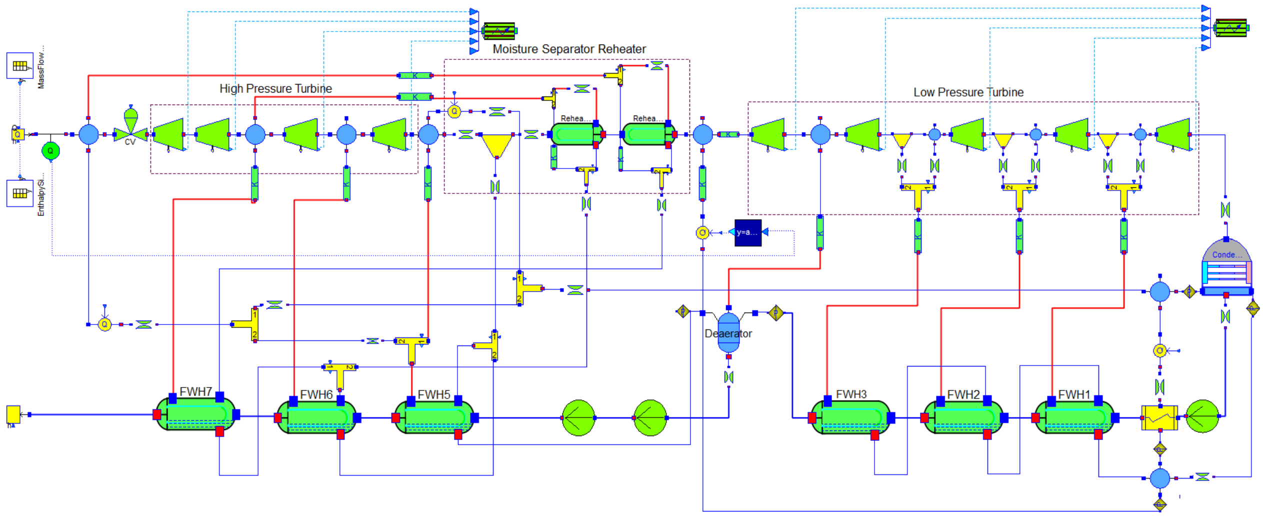


Fig.3. APR1400 secondary system model developed in OMEdit

where, E – energy of a system, $\dot{Q}$ – 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.

The APR1400 turbine performance is modeled applying the Stodola's ellipse law for each of the turbine stage groups defined as follows [5]:

$$\left(\frac{\dot{m}}{\dot{m}_{vwo}}\right)^2 = \frac{p_{in}^{\ 2} - p_{out}^{\ 2}}{p_{in,vwo}^{\ \ 2} - p_{out,vwo}^{\ \ 2}} \tag{2}$$

where, $\dot{m}$ – steam mass flow rate through a turbine stage group, $\dot{m}_{vwo}$ – steam mass flow rate through a turbine stage group at VWO condition, $p_{in/out}$ – steam pressure at the inlet/outlet of a turbine stage group, and $p_{in/out,vwo}$ – steam pressure at the inlet/outlet of a turbine stage groups at VWO condition.

The turbine stage group thermodynamic efficiency is calculated according to Eq. 3.

$$\eta = \frac{h_{in} - h_{out}}{h_{in} - h_{out,s}} \tag{3}$$

where, η – turbine stage group thermodynamic efficiency, $h_{in/out}$ – 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.

Additionally, the turbine stage group model is provided with a correction curve (Eq.4) to account for efficiency changes during off-design plant operation [5].

$$\eta = \eta_{vwo} - \left[ a\left(\frac{\dot{m}}{\dot{m}_{vwo}}\right)^3 + b\left(\frac{\dot{m}}{\dot{m}_{vwo}}\right)^2 + c\left(\frac{\dot{m}}{\dot{m}_{vwo}}\right) + d \right] \tag{4}$$

where, $\eta_{vwo}$ – turbine stage group thermodynamic efficiency at VWO condition, and a, b, c, d – cubic polynomial coefficients. The polynomial coefficients are determined based on turbine performance documented in the APR1400 design data [4]. Analogical fit curve is applied to the Stodola's coefficient (Eq.2) to benchmark the model against the reference data.

Furthermore, the following assumptions are made:

- Terminal Temperature Difference (TTD) and Drain Cooler Approach (DCA) for FWHs are fixed,
- condenser is an ideal heat sink,
- pumps provide constant head;
- Main Feedwater Pump (MFWP) turbines are not modeled, instead equivalent portion of steam necessary to drive the MFWP turbines is extracted and directed to the condenser,
- TES is modeled as a black box, the energy is transferred into or out of the APR1400 steam cycle at the interface connection points,
- S/G is not modeled.

## 4. Results and analysis

The APR1400 secondary cycle baseline simulation accuracy is shown in Figs.4 and 5. The simulation results of the APR1400 coupled with TES at three different interface configurations for charging and discharging operation using OM and PEPSE$^{TM}$ are compared in Table I.

Fig.4. shows relative error plotted against a ratio of a flow parameter value at given condition to its nominal value. The simulation is highly accurate at MGR and VWO conditions. At lower power levels higher values of the relative error can be observed. The biggest differences between simulation results and the design data are observed for the steam mass flow rates and pressures at ES lines supplying steam to MSR and FWH No.7. Nevertheless, out of 504 data points over 97% falls into relative error range of ±5%.

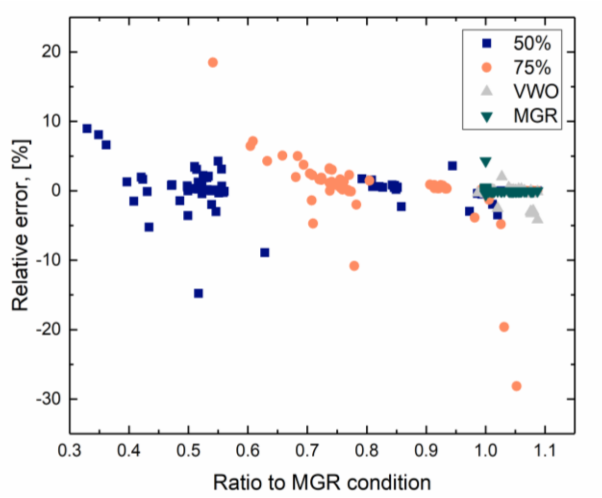


Fig.4. Relative error plotted against a ratio of flow parameters (mass flow rates, pressures and enthalpies) at given condition to their values at nominal condition.

The baseline OM simulation accuracy of the APR1400 turbine stage groups shaft power and generator power output is presented in Fig.5. The relative error for nominal and VWO conditions falls into the range of ±1% while for lower power levels the range is ±3%.

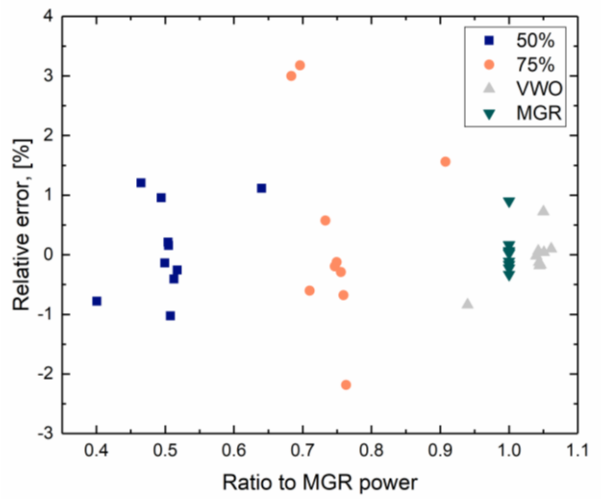


Fig.5. Relative error plotted against a ratio of turbine-generator power values (stage groups shaft power and generator power output) at given condition to their values at nominal condition.

The APR1400 Rankine cycle integrated with TES simulation results listed in Table I demonstrate that the OM model indicates similar performance as compared to the PEPSE$^{TM}$ simulation results published elsewhere [2]. The model developed in OM simulates quasi-steady state performance, hence a time-dependent behavior of the modeled cycle can be observed. PEPSE$^{TM}$ simulation capability is limited only to steady-state condition. Therefore, the OM model is advantageous considering that the cycle performance in the transition phase between the operating modes can be easily examined.

Table I: PEPSE and OM power output results comparison for Cases 1, 2 and 3.

| | Case No. | Power Output PEPSE [MW] [2] | Power Output OM [MW] | Relative Error [%] |
|---|---|---|---|---|
| TES Charging | 1 | 1145 | 1132 | -1.15% |
| | 2 | 1157 | 1145 | -1.04% |
| | 3 | 1171 | 1160 | -0.94% |
| TES Discharge | 1 | 1595 | 1591 | -0.23% |
| | 2 | 1585 | 1575 | -0.66% |
| | 3 | 1586 | 1581 | -0.32% |

## 5. Conclusions

The APR1400 secondary system model is developed using Modelica-based OM software. The model is validated against design data and used for investigation of APR1400 coupled with TES.

The OM baseline model accurately simulates APR1400 secondary system performance. The OM simulation of APR1400 integrated with TES indicates similar results as commercial software PEPSE$^{TM}$. It is considered that OM models are advantageous since the developed models simulate quasi-steady state conditions.

The work demonstrates that OM is promising tool for complex systems modeling, thus this software is suitable for evaluation of NPP flexible operation under integration with an external heat utilization facility.

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