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Validation of a program for supercritical power plant calculations

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Abstract This article describes the validation of a supercritical steam cycle. The cycle model was created with the commercial program GateCycle and validated using in-house code of the Institute of Power Engineering and Turbomachinery. The Institute's in-house code has been used extensively for industrial power plants calculations with good results. In the first step of the validation process, assumptions were made about the live steam temperature and pressure, net power, characteristic quantities for high- and low-pressure regenerative heat exchangers and pressure losses in heat exchangers. These assumptions were then used to develop a steam cycle model in GateCycle and a model based on the code developed in-house at the Institute of Power Engineering and Turbomachinery. Properties, such as thermodynamic parameters at characteristic points of the steam cycle, net power values and efficiencies, heat provided to the steam cycle and heat taken from the steam cycle, were compared. The last step of the analysis was calculation of relative errors of compared values. The method used for relative error calculations is presented in the paper. The assigned relative errors are very slight, generally not exceeding 0.1%. Based on our analysis, it can be concluded that using the GateCycle software for calculations of supercritical power plants is possible.

Keywords: Steam cycle; Validation; Supercritical power plant

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Nomenclature

i_{in} – enthalpy at the inlet to the turbine, kJ/kg
i_{out} – enthalpy in the blade or at the outlet from the turbine, kJ/kg
i_{out_s} – enthalpy of steam after isentropic expansion in blade or at the outlet from the turbine, kJ/kg
i_x – enthalpy at point x of the steam cycle, kJ/kg
$\dot{m}_x$ – flow of the water or steam at point x of the steam cycle, kg/s
$N_{el,G}$ – gross power of the power plant, kW
$N_{i_{HP}}$ – internal power of the high-pressure steam turbine, kW
$N_{i_{IP}}$ – internal power of the intermediate-pressure steam turbine, kW
$N_{i_{LP}}$ – internal power of the low-pressure steam turbine, kW
$\dot{Q}_{ch}$ – chemical energy stream of fuel, kW
$\dot{Q}_{CND}$ – heat discharged in the condenser, kW
$\dot{Q}_d$ – heat discharged from the steam cycle, kW
$\dot{Q}_{l,DA}$ – heat loss in the deaerator, kW
$\dot{Q}_{l,P}$ – heat loss in the live and the reheated steam pipelines, kW
$\dot{Q}_{l,RHE+SC}$ – heat loss in the regenerative heat exchangers and steam cooler, kW
$\dot{Q}_s$ – heat supplied to the steam cycle, kW
q_{ch} – specific consumption of chemical energy of fuel
q_q – specific consumption of heat
z_{GC} – value obtained using the model built in GateCycle
z_{IoPEaT} – value obtained using the model built with the in-house code of IoPEaT

Greek symbols

$\eta_{el,G}$ – gross overall efficiency
η_G – generator efficiency
η_i – isentropic efficiency
η_{sc} – efficiency of steam cycle
δ_z – relative error, %
ΔN_{mST} – mechanical losses in the steam turbine, kW

1 Introduction

Currently, there is a trend toward the use of commercial software for power plant steam cycle calculations. Software with integrated modules for computational algorithms representing different elements of the steam cycle, such as the steam turbine, deaerator, or regenerative heat exchanger, can shorter the time required to investigate power plant efficiency issues. These specialized computational programs have been successfully used (by our group and others) for the simulation of energy systems [1–4]. The possibility of using a broad spectrum of computational modules makes it possible to conduct research strictly on energetic problems as well as chemical engineering or economic issues. The intuitive user interfaces facilitate the design work.

However, despite the many advantages of commercial software, it must be emphasized that the uncritical use of these tools may lead to unexpected effects and unrealistic models. Using commercial software in research projects is advisable if we can be confident about the calculation methods used in the programs. Often though, the lack of such methodological information reduces the reliability of the results and impedes further calculations. The purpose of validation is to evaluate a developed model using commercial software and to accept or reject the model as a computational tool for the analysis of the planned project.

In the paper, we describe the validation of a steam cycle model built in GateCycle [5]. The model uses a steam cycle structure similar to the other structures used in these strategic projects. The in-house code developed at the Institute of Power Engineering and Turbomachinery (IoPEaT) [6] was used for validation of the model built in GateCycle, which has been used with success for several years for research purposes of the Institute.

2 Description of the steam cycle model and the assumptions used for analysis

For the purpose of validation, the steam cycle structure presented in Fig. 1 was adopted. The steam cycle consists of a boiler with a reheater (B), a steam turbine (consisting of a high-pressure part HP, an intermediate-pressure part IP, and a low-pressure part LP), an electric generator (G), a condenser (CND), a deaerator (DA), a condensate pump (CP), a feed water pump (FWP), seven regenerative heat exchangers (four low-pressure (LPH) and three high-pressure (HPH)) and a steam cooler (SC). The low-pressure regenerative heat exchangers are fed from the extractions of the intermediate- and low-pressure parts, while the high-pressure regenerative heat exchangers are fed from the extractions of the high- and intermediate-pressure parts of the steam turbine. It is assumed that the model of the steam cycle will not be used for computations involving variable loads [7].

The assumptions relating to the operational parameters for three variants are shown in Tab. 1. Gross power is calculated using the following equation:

$$N_{el_{,G}} = (N_{iHP} + N_{i_{IP}} + N_{i_{LP}} - \Delta N_{mST})\,\eta_G \ . \tag{1}$$

The gross power values for each part of the steam turbine are derived from the balance equations written for the group of stages located between individual inlets, extractions or outlets. The values of isentropic efficiencies are

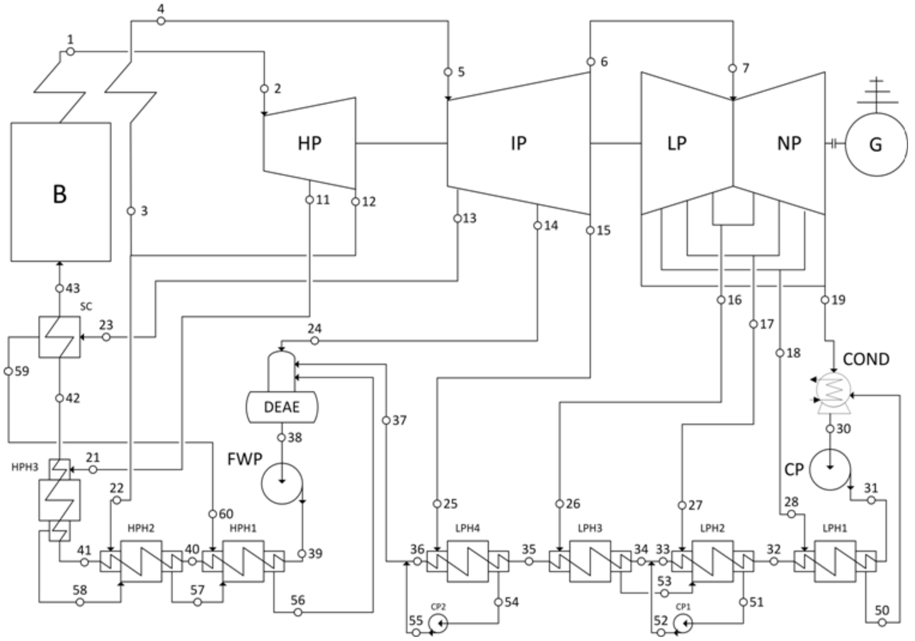

Figure 1. Diagram of a power plant steam cycle (B – boiler, HP – high pressure turbine, IP – intermediate pressure turbine, LP – low pressure turbine, CND – condenser, DA – deaerator, FWP – feed water pump, CP – condensate pump, LPH – low pressure feed water heater, HPH – high pressure feed water heater, SC – steam cooler).

calculated using the following equation:

$$\eta_i = \frac{i_{in} - i_{out}}{i_{in} - i_{out\_s}} \, . \tag{2}$$

The assumptions shown in Tab. 1 are based on current trends in the construction of modern coal-fired supercritical power plants [8,9]. They were used for the calculations performed on the steam cycle model built using the GateCycle software and the steam cycle model built using the in-house code from IoPEaT. In the GateCycle model, the pre-existing models of various steam cycle components were used. Of the assumed quantities listed in Tab. 1, only the gross power (Eq. (1)) determines the scale of a power plant. Based on this quantity, the steam flow of the model is determined. A specially implemented macro-script is used to calculate this steam flow in the algorithm.

Table 1. Characteristic quantities for the power plant under consideration.

Quantities	Symbols	Values	Unit
Gross power	$N_{el,G}$	460	MW
Temperature of live steam leaving the boiler and entering the steam turbine	t_1; t_2	604.9; 600.0	°C
Pressure of live steam leaving the boiler and entering the steam turbine	p_1; p_2	30.1; 29.0	MPa
Temperature of reheated steam leaving the boiler and entering the steam turbine	t_4; t_5	602.4; 600.0	°C
Pressure of reheated steam at the inlet of the steam turbine	p_5	4.8	MPa
Boiler energetic efficiency	η_B	94	%
Condenser operating pressure, deaerator operating pressure and pressure at the outlet of the condensate pump	p_{19}; p_{24}; p_{31}	0.005; 1.2; 1.6	MPa
Temperature of feedwater	t_{42}	297	°C
Isentropic efficiency of groups of stages of high-pressure, intermediate-pressure and low-pressure as well as the last group of stages of low-pressure steam turbine	η_{iHP}; η_{iIP}; η_{iLP}; η_{iLP1}	90; 93; 86; 81	%
Generator efficiency	η_G	99	%
Steam turbine mechanical losses	ΔN_{mST}	4.6	MW
Isentropic efficiency of pumps	η_{iP}	85	%
Efficiency of regenerative heat exchangers, steam cooler and deaerator	η_W; η_{SC}; η_{DA}	99.5	%
Pressure drop in steam pipeline to low-pressure and high-pressure regenerative heat exchangers, steam cooler and deaerator	ζ_{LPHi}; ζ_{HPHi}; ζ_{SC}; ζ_{DA}	2.0	%
Pressure drop in steam pipeline from steam cooler to HP1 regenerative heat exchanger	ζ_{59-60}	1.0	%
Pressure drop of water flowing through the low-pressure and high-pressure regenerative heat exchangers	ζ_{HPH}; ζ_{LPH}	6.0; 0.5	%
Pressure drop of working medium in boiler, steam in steam reheater, and steam in reheated steam pipelines	ζ_{42-01}; ζ_{03-04}; ζ_{12-03}; ζ_{04-05}	11.0; 3.0; 1.4; 2.4	%
Pressure drop between SP part and NP part of steam turbine	ζ_{06-07}	0.5	%
Temperature differences in low-pressure and high-pressure regenerative heat exchangers	ΔT_{sLPHi}, ΔT_{sHPHi}	3	K
Difference between temperature of condensate at outlet and temperature of water at inlet in low- and high-pressure regenerative heat exchangers	ΔT_{aLPHi}, ΔT_{aHPHi}	10	K
Increase of temperature of water in low-pressure regenerative heat exchangers	ΔT_{LPHi}	30	K
Increase of temperature of water in WP1, WP2 and WP3 regenerative heat exchangers	ΔT_{HPH1}; ΔT_{HPH2}; ΔT_{HPH3}	30.00; 37.04; 30.57	K
Increase of temperature of water in steam cooler	ΔT_{SC}	5	K

3 The results of validation

The results presented in this section were obtained using the steam cycle model built in GateCycle and using the model built-in the in-house code IoPEaT. Computations were performed using the assumptions presented in Tab. 1. To validate the steam cycle model built in the GateCycle software, the following quantities were examined: efficiency of steam cycle, gross overall efficiency, gross power, specific consumption of heat and specific consumption of chemical energy from fuel. To obtain the values of these evaluation indicators, the following parameters were determined: heat supplied to the steam cycle, heat discharged in the condenser, heat lost in the live and reheated steam pipelines and total amount of heat discharged from the steam cycle. The dependencies for the majority of these quantities are shown below.

The values calculated using Eqs. (4)–(9) and other equations, which are useful for comparing the results of computations performed using the two different models, are presented in Tab. 3. The quantity used to evaluate the model built in GateCycle was the relative error calculated for different thermodynamic parameters at the characteristic points marked in Fig. 1. The relative error is expressed by the following formula:

$$\delta_z = \frac{|z_{IoPEaT} - z_{GC}|}{z_{IoPEaT}} 100\% \; . \tag{3}$$

The efficiency of steam cycle is expressed by the following formula:

$$\eta_{sc} = \frac{\dot{Q}_s - \dot{Q}_d}{\dot{Q}_s} \; . \tag{4}$$

The formula for the gross overall efficiency is as follows:

$$\eta_{el,G} = \frac{N_{el,G}}{\dot{Q}_{ch}} \; . \tag{5}$$

The amount of heat supplied to the steam cycle is expressed by the following formula:

$$\dot{Q}_s = \dot{m}_1(i_1 - i_{42}) + \dot{m}_4(i_4 - i_3) \; . \tag{6}$$

The amount of heat discharged from the steam cycle is expressed by the following formula:

$$\dot{Q}_d = \dot{Q}_{CND} + \dot{Q}_{l,P} + \dot{Q}_{l,RHE+SC} + \dot{Q}_{l,DA} \; . \tag{7}$$

Table 2. The thermodynamics parameters at characteristics points of the steam cycle, calculated for both models, with relative errors.

Point	Model built in GateCycle				Model built using in-house code of IoPEaT				Relative error, %			
	t	p	m	i	t	p	m	i	δt (δx)	δp	δm	Δh
	°C (x,-)	kPa	kg/s	kJ/kg	°C (x,-)	kPa	kg/s	kJ/kg				
1	604.90	30100.0	336.07	3461.4	604.90	30100.0	336.04	3461.4	0.000	0.000	0.010	0.001
2	600.00	29000.0	336.07	3456.3	600.00	29000.0	336.04	3456.3	0.000	0.000	0.010	0.001
3	328.25	5070.1	284.43	3007.7	328.22	5072.0	284.39	3007.6	0.008	0.037	0.015	0.003
4	602.40	4918.0	284.43	3673.1	602.40	4918.0	284.39	3673.1	0.000	0.000	0.015	0.001
5	600.00	4800.0	284.43	3668.4	600.00	4800.0	284.39	3668.4	0.000	0.000	0.015	0.001
6	281.59	541.1	239.40	3025.4	281.52	541.2	239.38	3025.3	0.025	0.034	0.012	0.002
7	281.55	538.3	239.40	3025.4	281.48	538.5	239.38	3025.3	0.025	0.035	0.012	0.002
11	392.26	8162.2	25.60	3113.9	392.27	8165.2	25.60	3113.9	0.001	0.037	0.011	0.000
12	328.99	5142.1	310.47	3007.7	328.97	5144.0	310.43	3007.6	0.008	0.037	0.012	0.003
13	507.17	2747.7	17.46	3475.9	507.17	2748.6	17.46	3475.9	0.001	0.035	0.016	0.001
14	387.00	1224.5	15.09	3232.9	386.91	1224.5	15.09	3232.7	0.024	0.001	0.064	0.006
15	281.59	541.1	12.47	3025.4	281.52	541.2	12.47	3025.3	0.025	0.034	0.001	0.002
16	194.56	230.2	12.51	2858.3	194.48	230.3	12.51	2858.1	0.041	0.040	0.007	0.006
17	112.85	89.5	10.77	2703.3	112.77	89.6	10.77	2703.1	0.072	0.053	0.014	0.007
18	0.9646	26.7	11.54	2537.2	0.97	26.7	11.55	2537.0	0.038	0.091	0.060	0.006
19	0.9132	5.0	204.58	2350.5	0.91	5.0	204.55	2350.3	0.023	0.000	0.016	0.007
21	391.04	7999.0	25.60	3113.9	391.05	8001.9	25.60	3113.9	0.001	0.037	0.011	0.000
22	327.93	5039.3	26.04	3007.7	327.90	5041.2	26.04	3007.6	0.008	0.037	0.014	0.003
23	506.91	2692.7	17.46	3475.9	506.90	2693.7	17.46	3475.9	0.001	0.035	0.016	0.001
24	386.80	1200.0	15.09	3232.9	386.71	1200.0	15.09	3232.7	0.024	0.001	0.064	0.006
25	281.44	530.2	12.47	3025.4	281.37	530.4	12.47	3025.3	0.025	0.035	0.001	0.002
26	194.45	225.6	12.51	2858.3	194.37	225.7	12.51	2858.1	0.041	0.043	0.007	0.006
27	112.75	87.7	10.77	2703.3	112.67	87.8	10.77	2703.1	0.072	0.054	0.014	0.007
28	65.98	26.2	11.54	2537.2	66.00	26.2	11.55	2537.0	0.026	0.070	0.060	0.006
30	32.88	5.0	216.12	137.8	32.88	5.0	216.10	137.8	0.001	0.000	0.012	0.025
31	32.98	1600.0	216.12	139.7	33.00	1600.0	216.10	139.7	0.052	0.000	0.012	0.035
32	62.98	1504.0	216.12	264.9	63.00	1504.0	216.10	264.9	0.027	0.000	0.012	0.013
33	92.98	1413.8	216.12	390.6	93.00	1413.8	216.10	390.6	0.015	0.000	0.012	0.011
34	91.06	1413.8	239.40	382.5	91.07	1413.8	239.38	382.5	0.014	0.000	0.012	0.009
35	121.06	1328.9	239.40	509.1	121.07	1328.9	239.38	509.1	0.011	0.000	0.012	0.003
36	151.06	1249.2	239.40	637.3	151.07	1249.2	239.38	637.4	0.008	0.000	0.012	0.015
37	150.09	1249.2	251.87	633.1	150.12	1249.2	251.84	633.2	0.023	0.000	0.011	0.016
38	187.96	1200.0	336.07	798.5	187.97	1200.0	336.04	798.5	0.000	0.000	0.010	0.000
39	194.40	34505.2	336.07	843.1	194.42	34505.2	336.04	843.1	0.010	0.000	0.010	0.001
40	224.40	34332.6	336.07	974.2	224.42	34332.6	336.04	974.2	0.009	0.000	0.010	0.004
41	261.43	34161.0	336.07	1141.8	261.46	34161.0	336.04	1141.9	0.009	0.000	0.010	0.012
42	292.00	33990.2	336.07	1287.5	292.03	33990.2	336.04	1287.6	0.009	0.000	0.010	0.010
43	297.00	33820.2	336.07	1312.2	297.00	33820.2	336.04	1312.2	0.000	0.000	0.010	0.001
50	42.98	26.2	11.54	180.0	43.00	26.2	11.55	180.1	0.040	0.070	0.060	0.045
51	72.99	87.7	23.28	305.6	73.00	87.8	23.28	305.6	0.017	0.054	0.010	0.011
52	73.13	1600.0	23.28	307.4	73.15	1600.0	23.28	307.5	0.027	0.000	0.010	0.036
53	101.06	225.6	12.51	423.7	101.07	225.7	12.51	423.7	0.013	0.043	0.007	0.008
54	131.06	530.2	12.47	551.1	131.07	530.4	12.47	551.1	0.010	0.035	0.001	0.002
55	131.21	1600.0	12.47	552.4	131.24	1600.0	12.47	552.5	0.027	0.000	0.001	0.011
56	204.40	2665.8	69.10	872.6	204.42	2666.7	69.11	872.7	0.009	0.035	0.005	0.009
57	234.40	5039.3	51.64	1011.2	234.42	5041.2	51.65	1011.3	0.008	0.037	0.013	0.008
58	271.43	7999.0	25.60	1191.6	271.46	8001.9	25.60	1191.7	0.009	0.037	0.011	0.011
59	297.51	2692.7	17.46	2997.6	298.23	2693.7	17.46	2999.4	0.239	0.035	0.016	0.059
60	297.18	2665.8	17.46	2997.6	297.90	2666.7	17.46	2999.4	0.241	0.035	0.016	0.059

Table 3. Selected characteristic quantities obtained from the computations made using both models, along with calculated relative errors.

Quantities	Symbols	Model built in GateCycle	Model built using in-house code from IoPEaT	Unit	Relative error, %
Efficiency of steam cycle	η_{sc}	49.78	49.79	%	0.02
Gross overall efficiency	$\eta_{el,G}$	47.44	47.44	%	0.01
Gross power	$N_{el,G}$	460.0	460.0	MW	0.00
Specific consumption of heat	q_q	7133.8	7133.1	kJ/kWh	0.01
Specific consumption of chemical energy of fuel	q_{ch}	7589.2	7549.8	kJ/kWh	0.52
Heat supplied to the steam cycle	$\dot{Q}_s$	911542.1	911455.0	kW	0.01
Heat discharged in the condenser	$\dot{Q}_{CND}$	453172.5	453061.0	kW	0.02
Heat loss in the live and the reheated steam pipelines	$\dot{Q}_{l,P}$	3026.2	3025.8	kW	0.01
Heat discharged from the steam cycle	$\dot{Q}_d$	457772.4	457702.1	kW	0.02

The formula for the specific consumption of heat is as follows:

$$q_q = 3600\frac{\dot{Q}_s}{N_{el,B}} \ . \tag{8}$$

The specific consumption of chemical energy from fuel can be calculated based on the following formula:

$$q_{en\_ch} = 3600\frac{\dot{Q}_{ch}}{N_{el,B}} = \frac{q_q}{\eta_B} \ . \tag{9}$$

The relative error values calculated according to Eq. (3) are presented in Tabs. 2 and 3.

4 Conclusions

The results of validation prove that the task has been solved correctly. The relative error calculated according to Eq. (4) is within the range of accuracy ranging from 0.001 to 0.241%. The largest relative errors occur at values of temperature equal to 59 and 60, as shown in Fig. 1.

Based on validation results presented in Tabs. 2 and 3 and the analysis described above, steam cycle models built in GateCycle are acceptable as computational tools for investigating the steam cycles of supercritical power plants.

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