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Simulation model of 177 MW_e coal-fired double power unit

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Abstract. Model-based studies are widely used in the analysis and optimization of complex energy conversion processes in large thermal power plants. The creation and validation of a model of a power unit utilizing Bulgarian lignite enables us to study in detail the redistribution of heat flows in that unit. Along with the ability to optimize the thermodynamic cycle of energy generation, this research method enables us to conduct many study tasks that cannot be realized by conducting expensive and complex industrial experiments. The current article presents the creation of thermodynamic simulation model of a 4th power unit firing lignite coal in Maritsa East 2 TPP. Validation of the numerical solution was performed with data from the "Operating Instructions for the boilers", design heat balance calculations for steam turbine installation and performance test results onsite on two different loads.

1 Introduction

Thermodynamic simulation model-based studies as an analysis and optimization method of complex energy conversion processes, are widely used in large thermal power plants. The creation and validation of such models allows us to analyze the behavior of the plant even under technological scheme changes, which would be a very expensive (in some cases even impossible) industrial experiment.

In this article, a simulation model of the 4th power unit of TPP Maritsa- East 2 has been developed to study the operation of the plant from using Bulgarian lignite fuel Maritsa-East to natural gas and realizing a Combined Cycle (CCGT - combined gas turbine), with the available equipment - two boilers with one steam turbine and the associated flue gas cleaning installations (electrostatic filter (ESF) and desulfurization installation (SDG)).

The boilers are type PK-38-4M [1], originally designed for burning pre-dried lignite coal. In the process of exploitation of these facilities, it was decided to redesign them for utilization of non-dried local lignite with a calorific value of 5850-7100 kJ/kg, in the so-called "direct scheme", using milling fans by 4 independent coal preparation systems. Other features of these boilers are: “П” (U)-shaped arrangement, furnace of gas-sealed membrane screens, and forced circulation of the water-steam tract. This tract includes primary and intermediate superheat (high and intermediate steam pressure tract).

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Two boilers of the type above described, provide steam to a TCDF-36" steam turbine installation manufactured by Toshiba Corporation, and produces from 62 to 177 MWe. The low loads are achieved with single boiler operation. The turbine is a condensing type [2] and tri-casing design - high pressure turbine (HPT), intermediate pressure turbine (IPT) and two-flow low pressure turbine (LPT). Its regenerative system consists of two condensing heat exchangers (HX1 and HX2), four low-pressure heaters (LPH1, LPH2, LPH3, and LPH4), one deaerator (D), and three high-pressure heaters (HPH5, HPH6, and HPH7). The fluid flow is provided by two condensate (low-pressure) pumps and one feeding (high-pressure) pump.

2 Simulation environment

The simulation environment used to model the power double unit described above is Thermoflex, part of Thermoflow Inc portfolio.

Thermoflow is the leading developer of thermal engineering software for the power and cogeneration industries. Since 1987, Thermoflow's software product line has grown to become the most popular, well-proven, and comprehensive system available today. Thermoflex is a general purpose program for design & simulation of gas turbine combined cycles [3], cogeneration systems, conventional steam plants, renewable energy, and other thermal systems [4,5,6].

The Thermoflex program is relatively easy to use compared to other similar heat balance programs. It does not require the user to enter a number of initial values or special code or scripts. The program uses a hierarchical approach. Based on pressure and flow data input, it generates a solution for any common type of power plant or cogeneration plant using logic components. For more advanced users, the program provides the ability to override hierarchies and use custom scripts. In this way, flexibility is increased and it is better adapted to the needs of the user.

Thermoflex combines a graphical interface with accurate, analytical models of power plant processes in terms of thermodynamics, heat transfer and fluid mechanics. This allows the user to design and investigate by simulation, complex process schemes.

The software uses two basic principles when reproducing a specific real object into a simulation model - design and off-design modes. The design is performed directly by selecting the gear icons from the library, then linking them graphically. A logic check ensures that the connections are made correctly. Once the flowchart is built, the specific characteristics of the facilities are entered.

Each model can have an unlimited number of cases and each case can be in design mode, calculating the physical side (and other parameters) of the facilities. The cases can also be calculated in off-design modes, analyzing the effect of parameter changes on the plant. Varied analyses can be done based on the results obtained from models such as:

- Full performance cycle analyzing of energy systems, giving operational characteristics information of each flowchart point, including the overall energy generation efficiency [7] and generated carbon emissions [8].
- Simulating off-design operation of existing systems in working conditions
- Predicting the effect of any changes made to individual facilities on the performance of the entire system [9,10], etc.

3 Results of power unit modeling and verification

The power unit simulation model was created in two stages. In the first, the two boilers [1] and the steam turbine [2] with the regenerative system were modelled separately, and in the second stage, the two models were merged to form the power unit [3,4].

3.1 Modeling of boilers PK-38-4M

The once-through PK-38-4M boilers described above have a total of 11 heating surfaces. Of these, one is economizer, two are evaporative (lower radiation heater and transition zone), six are superheaters (4 for live steam and 2 for reheated steam) and two for tubular air heater. The live steam is regulated by two feedwater sprays (desuperheaters) and the intermediate superheated steam by bypassing the first reheating surface (RH-1). The arrangement of heating surfaces and flows diagram (live and reheated steam tracts, flue gas tract, combustion air tract, etc.) are shown in Figure 1.

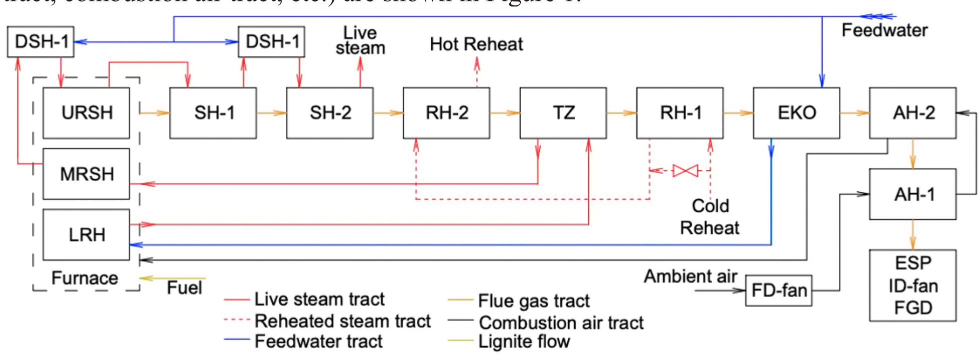


Fig. 1. The arrangement of heating surfaces and flows diagram of boiler type PK-38-4M

A total of 65 components were used to build the model of the two steam generators as follows:

• 2 furnace chambers in which, in addition to the evaporative heating surfaces (lower radiation heater (LRH) from the actual furnace), two additional steam superheaters are included – middle and part of the upper radiation superheaters (MRSH and URSH).

• 12 superheaters for live and reheated (intermediate superheating) steam;

• 2 heating surfaces for the transition zones (TZ) of both boilers;

• 2 economizer heating surfaces;

• 4 tubular air heaters (two per boiler to model the two stages of a real air heater);

• 4 desuperheaters: between the MRH and the URH and between the Superheater-1 (SH-1) and the SH-2 for both boilers;

• 6 temperature controllers: 2 pcs. simulating the operation of reheated steam controllers, 2 pcs. in front of the forced-draft (FD) fans and 2 pcs. simulating the mixers between the two stages of the air heaters;

• 4 fans - 2 pcs. FD-fans and 2 pcs. induced-draft (ID) fans;

• 19 mixers and 10 splitters;

• 2 components for ESP, one 1 wet FGD, and a stack (chimney).

The model boundary conditions are given by the actual areas of the heating surfaces, the size and configuration of the tubes, the saturated steam flow rate (232 t/h) and the lignite quality shown in Table 1.

Table 1. Proximate analysis of used coal (as received).

Volatile Matter, %	Fixed Carbon, %	Ash, %	Moisture, %	LHV, kJ/kg
19.05	12.70	17.25	51.00	6559

Next Figure 2 shows the assembled model. For clarity, it is divided into two parts: the first covers the water-steam tracts and convective shafts (part of the flue gas tract), and the second covers the combustion air and the rest of the flue gas tracts.

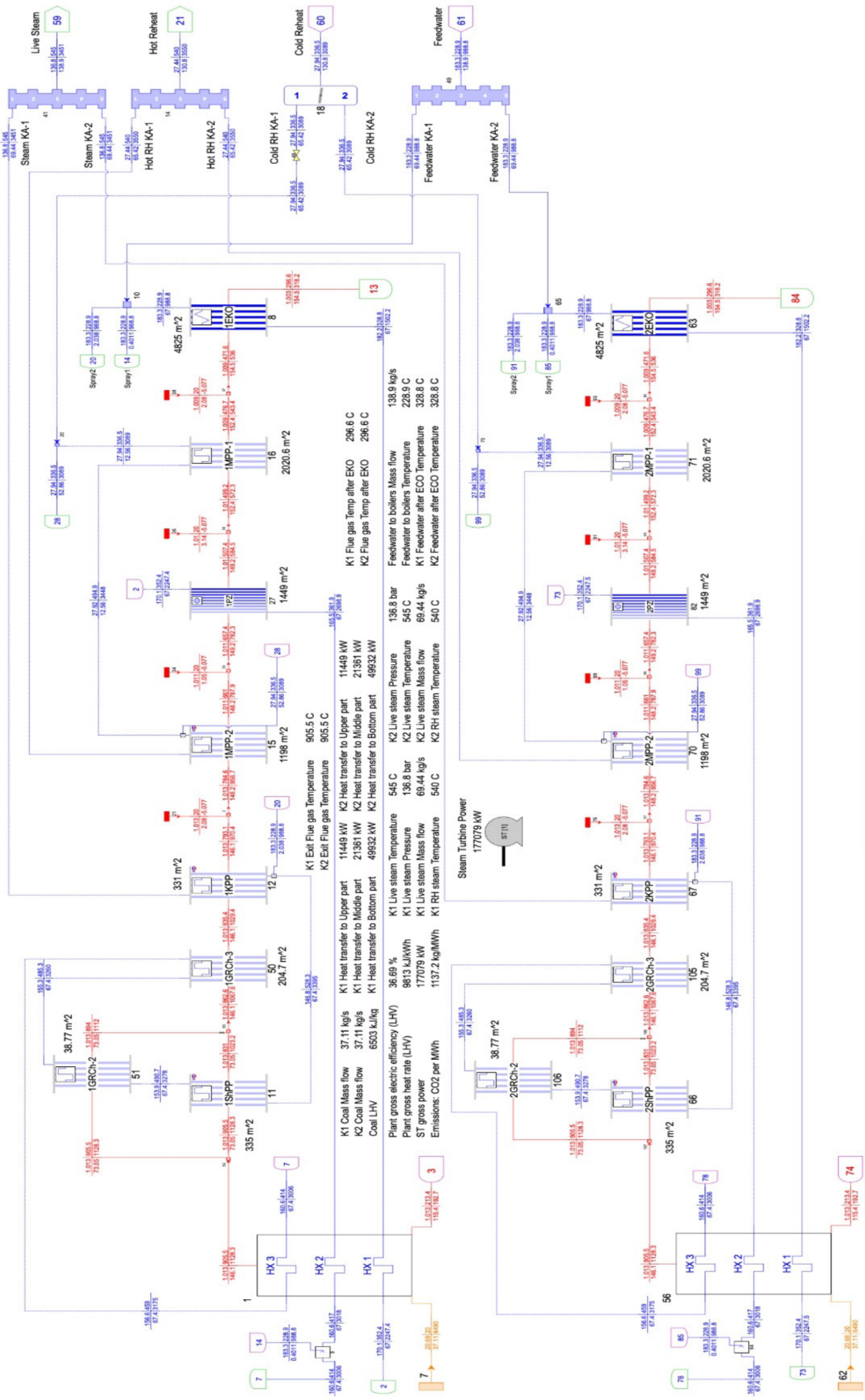
As a result, the model produces a large database with parameters for all flows and components used. Validation of the numerical solution was performed with data from the "Operating Instructions for PK-38-4M Boilers". Part of the comparative analysis at maximum load is shown in Table 2.

Table 2. Validation of the boiler model.

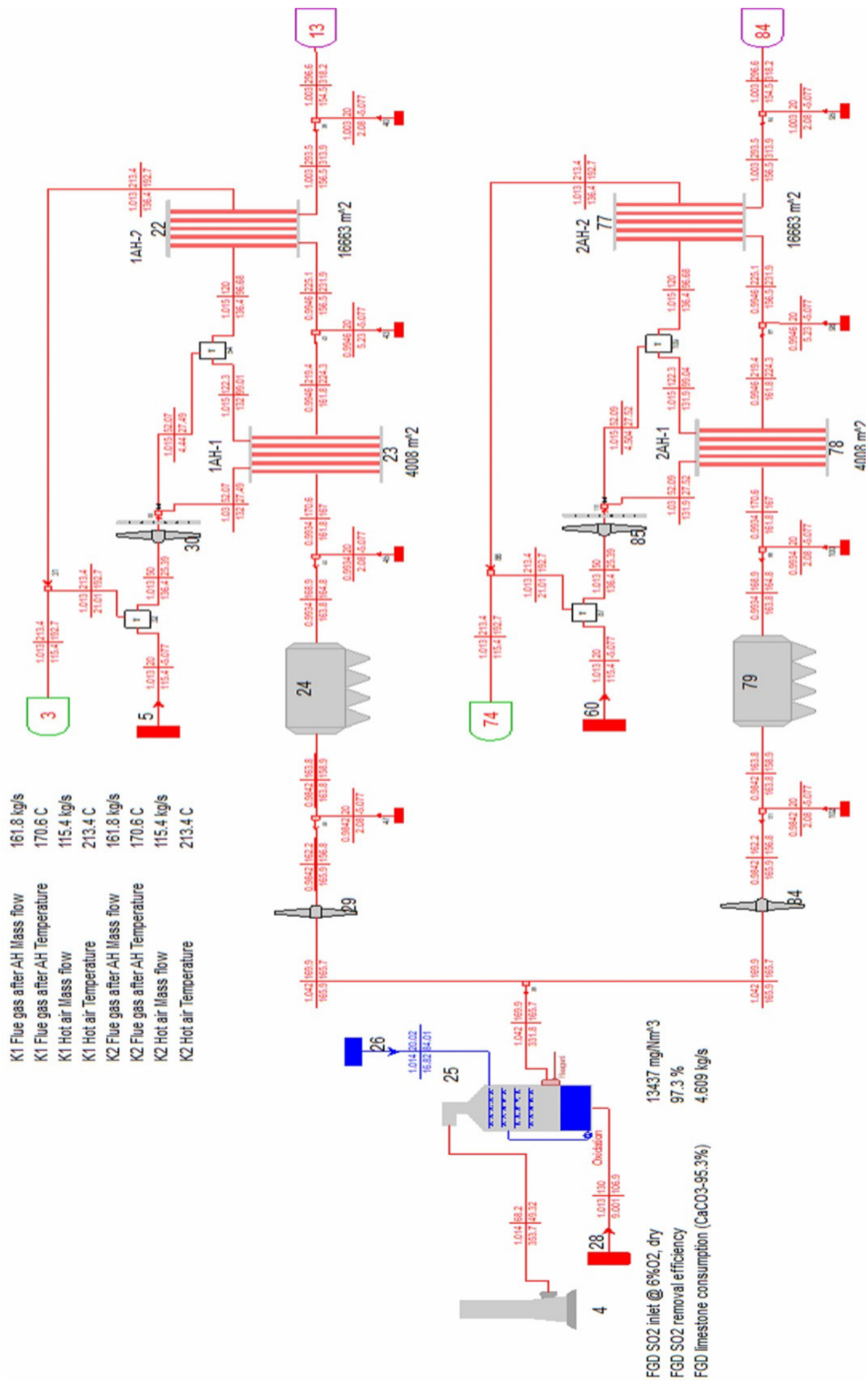
Parameter	Dimension	Instruction	Model	Difference
$t_{feedwater}$ / t_{ECO}^{in}	°C	230	229	-0.4%
$p_{feedwater}$ / p_{ECO}^{in}	MPa	18.3	18.33	0.2%
$m_{feedwater}$ / m_{ECO}^{in}	kg/s	63.89	67	4.6%
t_{EKO}^{out} / t_{LRH}^{in}	°C	338	329	-2.7%
t_{LRH}^{out} / t_{TZ}^{in}	°C	350	352	0.6%
t_{TZ}^{out} / t_{MRSH}^{in}	°C	368	362	-1.7%
t_{MRSH}^{out} / t_{DSH-1}^{in}	°C	435	417	-4.3%
t_{DSH-1}^{out} / t_{URSH}^{in}	°C	405	414	2.2%
t_{URSH}^{out} / t_{SH-1}^{in}	°C	489	491	0.4%
t_{SH-1}^{out} / t_{DSH-2}^{in}	°C	525	528	0.6%
t_{DSH-2}^{out} / t_{SH-2}^{in}	°C	506	503	-0.6%
t_{SH-2}^{out}	°C	545	545	0.0%
p_{SH-2}^{out}	MPa	13.7	13.68	-0.1%
m_{SH-2}^{out}	kg/s	69.44	69.44	0.0%
$t_{ColdReheat}$	°C	336	337	0.3%
$t_{HotReheat}$	°C	540	540	0.0%

3.2 Modeling of steam turbine installation TCDF-36”

The steam turbine TCDF-36" is a single shaft condensing unit with a rotation frequency of 3000 min^{-1} in a three casing design - one high pressure cylinder (HPC or HPT), a second intermediate pressure cylinder (IPC or IPT) and a third low pressure cylinder (LPC or LPT), with an electrical output of 177 MW at a live steam consumption of 480 t/h with parameters of 127.5 bar and 545 °C. After the HPT the steam is returned to the boiler for secondary superheating (reheating) and fed to the IPT with parameters 27.5 bar and 540 °C. The turbine has eight non-regulated steam extraction ports feeding the regenerative system. The first extraction port is after HPT, the 2nd, 3rd, and 4th are in IPT, the 5th is between IPT and LPT,


Live Steam
Hot Reheat
Cold Reheat
Feedwater
Steam KA-1
Steam KA-2
Hot RH KA-1
Hot RH KA-2
Cold RH KA-1
Cold RH KA-2
Feedwater KA-1
Feedwater KA-2
K1 Coal Mass flow 37.11 kg/s
K2 Coal Mass flow 37.11 kg/s
Coal LHV 6503 kJ/kg
K1 Heat transfer to Upper part 11449 kW
K1 Heat transfer to Middle part 21361 kW
K1 Heat transfer to Bottom part 49932 kW
K1 Exit Flue gas Temperature 905.5 C
K2 Exit Flue gas Temperature 905.5 C
K2 Heat transfer to Upper part 11449 kW
K2 Heat transfer to Middle part 21361 kW
K2 Heat transfer to Bottom part 49932 kW
K1 Flue gas Temp after EKO 296.6 C
K2 Flue gas Temp after EKO 296.6 C
Plant gross electric efficiency (LHV) 36.69 %
Plant gross heat rate (LHV) 9813 kJ/kWh
ST gross power 177079 kW
Emissions: CO2 per MWh 1137.2 kg/MWh
K1 Live steam Temperature 545 C
K1 Live steam Pressure 136.8 bar
K1 Live steam Mass flow 69.44 kg/s
K1 RH steam Temperature 540 C
K2 Live steam Pressure 136.8 bar
K2 Live steam Temperature 545 C
K2 Live steam Mass flow 69.44 kg/s
K2 RH steam Temperature 540 C
Feedwater to boilers Mass flow 138.9 kg/s
Feedwater to boilers Temperature 228.9 C
K1 Feedwater after ECO Temperature 328.8 C
K2 Feedwater after ECO Temperature 328.8 C
Steam Turbine Power 177079 kW

(a)



(b)

Fig. 2. Model of two boilers type PK-38-4M: (a) furnaces and convective shafts; (b) combustion air and the rest of the flue gas tracts.

and the rest (6th, 7th, and 8th) are in LPT. These eight steam extractions conditionally divide the turbine into nine sections. The condenser of the turbine is a surface condenser type with a heat exchange surface of 9300 m^2, two-flow and two-pass circulating water.

The regenerative system consists of two condensing heat exchangers, four low-pressure preheaters (each with 250 m^2 heating surface) and three high-pressure preheaters (each with 425 m^2 heating surface). The deaerator working pressure is 4.7 bar, and acts as a mixing type preheater in the low pressure section. After it, the feedwater pumps raise the pressure, covers hydraulic losses to the steam turbine.

To create the steam turbine installation model, a total of 23 Thermoflex's components were used, as follows:

• 1 steam turbine module including: tri-casing turbine (high, intermediate, and low pressure), control valves, 7 non-regulated steam extractions, generator, and steam sealing system;

• 1 condenser with source and sink for circulation water;

• 2 condensing heat exchangers;

• 4 low-pressure heaters (LPH), one deaerator (D), and 3 high-pressure heaters (HPH) with desuperheater steam and drain cooler section;

• 3 pumps: two low-pressure/condensate pumps and one high-pressure/feeding pump;

• 1 pipe for pressure drop simulation between boilers and steam turbine;

• 4 mixers, 2 splitters and 1 component for makeup water.

The system was assembled according to a process flow diagram from Toshiba, and the model itself is presented in Figure 3.

Validation of the established model was performed with data from Toshiba's heat balance calculations. Table 3 shows part of the comparative analysis performed.

Table 3. Validation of the steam turbine model

Energy input/received	Heat balance, kWh	Model, kWh	Difference
to High-pressure turbine	459453	461467	0.44%
to Intermediate-pressure turbine	445243	442100	-0.71%
to HPH-3	13296	13807	3.70%
to HPH-2	22674	22985	1.35%
to HPH-1	20638	20393	-1.20%
to LPH-4	12161	11725	-3.72%
to LPH-3	11663	11295	-3.26%
to LPH-2	17355	17927	3.19%
to LPH-1	8614	8632	0.21%
Generated electricity	177370	177332	-0.02%

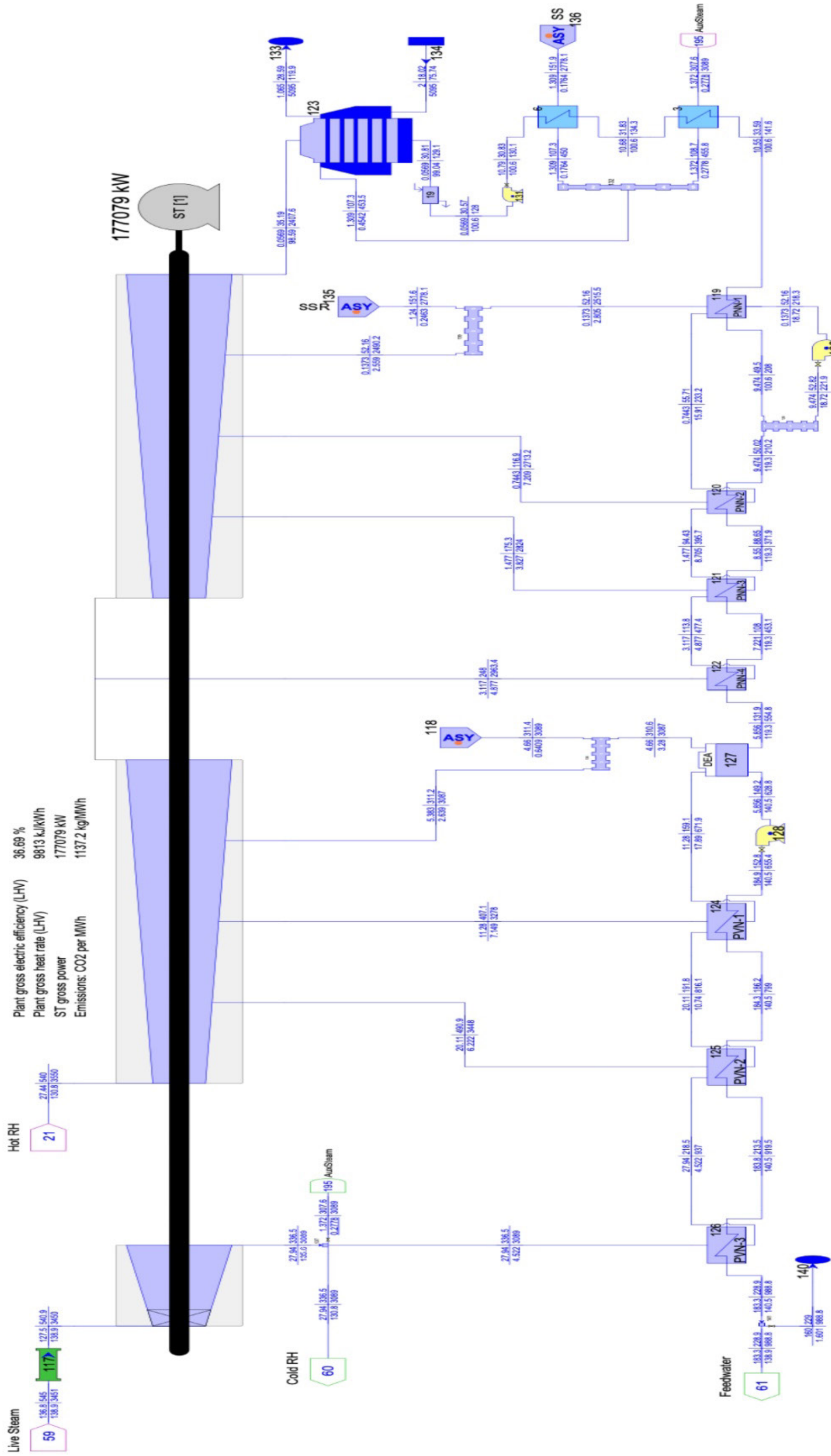


Fig. 3. Model of TCDF-36” steam turbine installation.

3.3 Assembled model validation of the power unit

Through the combined use of the two models described above, the general synthesized model for the operation of power unit No. 4 in TPP Maritsa-East 2 is formed. The validation of the synthesized model was carried out using the data obtained from the performed simulations and the operation of the two boilers of power unit No. 4 in TPP Maritsa-East 2 at maximum and minimum load. The results of the comparative analysis are presented in Table 4.

Table 4. Comparative analysis between experimental and model data for the power unit No 4.

Parameter	Source / difference	Max load	Min load
Power generation, MWe	Real data	177	135
	Model	177.3	136
	Difference	0.17%	0.74%
Net el. efficiency, %	Real data	36.69	34.55
	Model	36.45	34.4
	Difference	-0.65%	-0.43%
Net heat rate, kJ/kWh	Real data	9813	10024
	Model	9755	9981
	Difference	-0.59%	-0.43%
Specific CO_2 generation, $kgCO_2/MWh$	Real data	1145	1222
	Model	1137	1211
	Difference	-0.70%	-0.90%

4 Conclusion

From the presented validation of the numerical solution, it is shown that the created thermodynamic model of the 4th power unit in TPP "Maritsa East 2" reproduces with high fidelity the operation of the real object. The use of such models allows a quick and reliable study of the unit performance, whether it is a change of a parameter (for example fuel quality, saturated steam flow rate, area of heating surface etc.) or even a change in the technological scheme (by removing a heater or adding a gas turbine for example).

The created model will be used for subsequent study of the possibility of realizing a Combined cycle (CCGT – combined-cycle gas turbine), with the available equipment of the modeled power unit, by changing the fuel base (from coal to natural gas) and by including a gas turbine in the technological scheme. This would lead to an efficiency increase of the power generation cycle and, consequently, to a significant reduction in CO_2 emissions to the environment. The basis for this future study is the fact that the steam turbine installation of the unit (as well as those of Units 1 and 3 in TPP Maritsa East 2) is relatively new, has a significant operational resource, and operates at relatively high techno-economic factors.

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