Study of TGM-94 boiler with variable feed water temperature using a calculation model

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Abstract. The article substantiates the need to test performance capability and effectiveness of a steam boiler in the new conditions under any changes in the regenerative heating circuit of the feed water in a steam turbine plant. Such changes may include: the displacement of steam extractions on high pressure feed water heaters by the sun, by heat from biomass or garbage burning, or by steam from third-party sources. For this purpose we have developed a mathematical model of the steam boiler TGM-94 from steam turbine installation K-150-130. The model was created with Boiler Designer program. Verification of the calculated and experimental data provided by Krasnodar TTP showed sufficient convergence in both the steam-water and gas paths. We observed differences in the following temperatures: feed water temperature after the first stage of the economizer, flue gases and air temperature at the inlet to the furnace. The maximum difference between calculation and experiment here is 6 °C. We studied the boiler operation at a variable load, but with a constant temperature of the feed water equal to the nominal value of 230 °C. It was shown that in order to work in this mode, and in order to maintain the superheat temperature of the primary and secondary steam, it is necessary to turn on the flue gas recirculation smoke exhausters. We studied the operation of the boiler at a reduced feed water temperature. It turned out that such work leads to a decrease in steam production, if we keep the fuel consumption unchanged. In the case of sustaining steam production, it is required to assess the temperature state of the heating surfaces additionally due to a significant increase in the superheat temperature of both the primary and secondary steam.

1. Introduction

Modern power industry is characterized by an increase in the share of electricity generation through alternative energy sources. The European Union has set a plan to achieve a share of renewable electricity equal to 97% by 2050 [1]. Despite the fact that there is a development of “green” and distributed generation [2, 3], the basis of the energy sector in most countries is still made up of powerful thermal power plants [4]. The development vector of Chinese generation facilities is also shifting towards alternative sources [5], although a significant percentage of their energy still falls at coal steam turbine plants [6].

An increase in the share of solar and wind power plants leads to an increase in the unevenness of the daily schedule of electrical loads and this requires an increase in the maneuverability of the power system. To control the frequency in some countries, even coal-fired steam turbine plants have to be used [6]. Therefore, a significant amount of scientific research in recent years has been devoted to
various methods for increasing peak power and expanding the regulatory range of steam turbine power units.

Nowadays there is a number of research in the field of deeper cooling of flue gases in steam boilers of steam turbine plants by installing an additional economizer [6, 7, 8, 9, 10]. There are solutions on the use of heat obtained by burning biomass [11] or garbage [12] at thermal power plants with steam turbine plants. The authors developed a technology for the joint operation of steam-turbine and combined-cycle plants [13, 14]. According to preliminary calculations, the application of such a solution in the conditions of the Krasnodar TPP leads to an increase in the maximum electric capacity of the power plant by 3.2 MW [15].

All methods for increasing the peak power and expanding the control range of the steam turbine plants that have been considered affect the temperature of the feed water in front of the steam boiler. This in turn changes the efficiency of the boiler unit. To assess the impact of certain decisions on the operation of a power plant, it is necessary to develop accurate mathematical models of steam boilers.

The issues of modeling processes in energy steam boilers require the use of modern software products. There is a wide range of such programs. Let's consider some of them. In the works of Liu et al., the software product HYSIS was used to simulate combined cycle plants [16, 17]. In their article on high-efficiency power units, Zhao et al. used two GSE Systems software tools called JTopmeret and JControl [6] to model processes in a steam boiler of a power plant. Combined cycle plant with a recovery boiler was simulated using the Thermolib application for the MatLab Simulink software package in the work of Usova S.V. and Kudinova A.A. [18]. Using the program Boiler Designer Sidorkin V.T. et al. simulated a steam boiler of a power plant to study the effect of solid fuel composition on its efficiency [19]. A. Moshkarin, and Melnikov Yu.V. studied the operation of a combined cycle gas turbine unit at partial loads with this software [20]. All these software products have their advantages and disadvantages, but they adequately correspond to the task of modeling the equipment of thermal power plants.

This article sets the task to develop and verify the mathematical model of the TGM-94 steam boiler with Boiler Designer software product. Using this model we want to assess the effect of changes in feed water temperature at the boiler inlet on its key parameters. In the future, it is planned to use the developed model for research related to the schemes of joint operation of steam-turbine and combined-cycle power units.

2. Description of study object, the mathematical model of the steam boiler and its experimental verification

The Krasnodar TPP was chosen as the study object. To date, its equipment is represented by four K-150-130 steam-turbine units manufactured by Kharkov Turbogenerator Plant (KhTGP) (three of which were reconstructed into T-145 / 160-130 models by organizing controlled heat extraction in them) and by combined cycle plant PGU-410. The latter is a three-circuit binary combined cycle gas plant built on the basis of a gas turbine unit of M701F4 type manufactured by Mitsubishi Heavy Industries, Ltd (Japan).

Let us consider the object of simulation - the steam boiler TGM-94 (EP-500/140) of power unit No. 4. Its schematic diagram is shown in figure 1. Here, we didn’t indicate the front, bottom and rear firebox screens for simplicity. Of all the surfaces of the wall economizer, we indicated only the one located on the inclined wall of the rotary chamber. We also didn’t display superchargers on the diagram: fans and smoke exhausters.

The mathematical model was developed in the Boiler Designer program. Its advantages include both detailed thermal and hydraulic calculation of all elements. At the same time, well-tested standard methods are used to calculate heat transfer coefficients in smooth-tube and finned bundles, shell-and-tube heat exchangers with partitions and in other places. It is also important that there is the possibility to create controlled and all-mode models.

At the first stage of mathematical model development, we drew up a steam boiler diagram and set the parameters of its elements in accordance with the manufacturer's data. We set the following
parameters: the sequence of heat-exchange surfaces along the gas and steam-water paths, their geometric dimensions, material, thermal efficiency coefficients, etc. The simulation results showed sufficient convergence with the factory calculation. The design schemes of the gas and steam-water paths are presented in figures 2, 3.

**Figure 1.** Schematic diagram of the steam boiler TGM-94.  
1 – drum, 2 – radiation superheater, 3 – ceiling superheater, 4 – screen superheater, 5 – convective superheater, 6 – first stage of the secondary superheater, 7 – second stage of the secondary superheater, 8 – economizer (two steps), 9 – regenerative air heater 10 – suspended pipes, 11 – installation of internal condensate, 12 – wall economizer, 13 – screen furnace tubes, 14 – recirculation gas flue.

**Figure 2.** The design scheme of the gas path of the boiler TGM-94.
Figure 3. The design scheme of the steam-water path of the boiler TGM-94.

The mathematical model verification was carried out according to the data for the boiler of power unit No. 4 provided by the Krasnodar TPP: mode map of the boiler and measurement results of the oxygen content at different points of the gas path, the temperature of flue gases, the temperatures of water and steam over different heating surfaces. Measurements were provided for four modes with different steam capacities (250, 340, 400, 440 t / h) when working on natural gas. Using these data, the mathematical model was tuned. We adjusted the efficiency coefficients of convective heating surfaces, suction cups along the gas path of the boiler, the furnace parameter M, characterizing the position of the torch in the furnace, and a number of other parameters. The results of comparing the calculated and experimental data are given in table 1. The pressure of sharp steam is assumed to be 12.75 MPa, the inlet air temperature is 30 °C.

Table 1. Comparison of calculation results using a mathematical model and measurement for a TGM-94 boiler of unit No. 4 of the Krasnodar TPP.

| Parameter                                      | Boiler load, t / h | 250  | 340  | 400  | 440  |
|------------------------------------------------|-------------------|------|------|------|------|
| Temperature of superheated steam, °C            | Calcul.           | 542  | 542  | 542  | 542  | 545  | 545  |
| Pressure in a drum, MPa                         | Measur.           | 542  | 542  | 542  | 542  | 542  | 542  |
| Secondary steam consumption, t / h              | 14.02             | 14.02| 14.47| 15.00| 15.00| 15.20| 15.20|
| Secondary steam temperature at the inlet, °C   | 530               | 530  | 528  | 528  | 535  | 535  | 538  | 538  |
| Feed water temperature at the boiler inlet, °C | 200               | 210  | 217  | 223  |      |      |      |
| Feed water temperature after the first stage of the economizer, °C | 263               | 260  | 265  | 270  | 270  | 279  | 275  |
| Steam temperature after radiation superheater, °C | 370               | 370  | 369  | 368  | 370  | 370  | 372  | 373  |
| Steam temperature after ceiling superheater, °C | 381               | 380  | 384  | 383  | 384  | 385  | 390  | 390  |
| Steam temperature after a screen superheater, °C | 470               | 470  | 472  | 472  | 471  | 472  | 470  | 470  |
| Steam temperature after the first stage of convective superheater, °C | 497               | 498  | 499  | 498  | 493  | 500  | 498  |
| Flue gas temperature in front of the air heater, °C | 327               | 329  | 332  | 332  | 340  | 338  | 344  | 343  |
| Flue gas temperature after the air heater, °C   | 148               | 150  | 148  | 147  | 145  | 148  | 146  | 149  |
| Air temperature after an air heater, °C         | 295               | 301  | 299  | 303  | 303  | 305  | 306  | 310  |

These input parameters are common for calculation and measurement, as they were taken as initial data.
These results show that the developed model fully reflects the processes occurring in the steam boiler. The most significant differences are observed in temperature values: feed water after the first stage of the economizer, flue gases and air at the inlet to the furnace. The maximum difference between calculation and experiment here is 6 °C. This may be due to measurement error and imperfection of mathematical modeling methods. We consider the obtained accuracy sufficient to assess the influence of external effects on the efficiency of the steam boiler.

3. The study results of the changes in the feed water temperature on the operation of the boiler TGM-94

It is known that when the load of a steam turbine power unit is reduced, the pressure in regenerative extraction decreases. This also leads to a decrease in the temperature of the feed water at the inlet to the boiler. But if an external source of heat is used to heat the feed water, then this temperature will not change. Let us consider the operation mode of the boiler TGM-94 of power unit No. 4 of the Krasnodar TPP, when in the entire load range the temperature of the feed water will be equal to the nominal value of 230 °C. The study was carried out using the mathematical model described above. Most parameters remained constant or changed slightly, including efficiency. But an increase in feed water temperature led to a decrease in fuel consumption (figure 4). This, in turn, had an effect on the rate of combustion products in the convective part. The temperatures of superheated and secondary steam decreased (figure 5, 6).

![Figure 4. The dependence of fuel consumption on the load.](image)

The results of the study suggest that in the case of maintaining the temperature of the feed water due to the heat of a third-party source, it will be necessary to turn on flue gas recirculation smoke exhausters to maintain the superheat temperature of the primary and secondary steam.

Besides, when using third-party heating of feed water in order to increase the maximum power of the power unit, it is possible that in the nominal mode the feed water will not be heated to the required value. Using the mathematical model described above, we studied the operation of the TGM-94 steam boiler with a variable temperature of the feed water at the entrance to it. We calculated the two modes: 1. Fuel consumption remains constant, equal to the nominal; 2. Nominal steam capacity is maintained (500 t/h) due to changes in natural gas consumption. The most significant research results are shown in figures 7 and 8.
In the boiler operation mode with a reduced feed water temperature at the inlet and constant fuel consumption, we observed an increase in efficiency by 0.3%. At the same time, steam production decreases from 500 to 453 t/h with a change in feed water temperature from 230 to 170 °C. A decrease in steam production of 47 t/h will significantly affect the capacity of a steam turbine. When working in such conditions, there is a significant increase in injection for cooling superheated steam, while the temperature of the secondary steam remains almost unchanged.

![Figure 5. The dependence of the superheated steam temperature from the load.](image1)

![Figure 6. The dependence of the secondary steam temperature from the load.](image2)

![Figure 7. Dependence of boiler efficiency on feed water temperature.](image3)

![Figure 8. The dependence of the water flow rate for injection to cool the hot steam from the feed water temperature.](image4)
In the operation mode of the boiler with a reduced feed water temperature at the inlet and while maintaining a constant steam production, the efficiency is almost constant. The change is less than 0.1%, which is in the error zone. But there is an increase in fuel consumption from 42.5 to 47.7 thousand nm3 / h with the same change in feed water temperature. To implement such a regime, an additional performance assessment of the burner devices will be required. In addition, the temperature of both superheated and secondary steam rises significantly. The latter requires devices not only for emergency injection, but also for organizing an additional system for monitoring the temperature of the secondary steam. At a feed water temperature of 160 ºС, the temperature of superheated steam goes beyond permissible limits, since the possibilities of installing internal condensate, which produces condensate for organizing the injection, are exhausted. In addition, a supplementary assessment of the temperature state of the metal on the heat-exchange surfaces is required in order to verify the reliability of their work in such conditions.

4. Conclusions

In this work, we developed a mathematical model of the steam boiler TGM-94 steam turbine installation K-150-130 was developed. The model was created using a software product Boiler Designer.

Verification of the mathematical model with real data obtained during the operation of power unit No. 4, operating as part of the Krasnodar TPP, showed sufficient convergence in terms of coolant temperatures along both the steam and gas paths. We observed the most significant differences in temperature values: feed water after the first stage of the economizer, flue gases and air at the inlet to the furnace. The maximum difference between calculation and experiment here is 6 ºС. This may be due to measurement error and imperfection of mathematical modeling methods.

We studied the operation of the TGM-94 boiler at a variable load, but with a constant temperature of feed water equal to the nominal value of 230 ºС. It was shown that an increase in feed water temperature leads to a decrease in fuel consumption by 1.74 thousand nm3 / h. This affects the speed of the combustion products in the convective part and reduces the temperature of the superheated and secondary steam. To work in this mode, the flue gas recirculation smoke exhausters will be required to maintain the superheat temperature of the superheated and secondary steam.

We researched the operation of the TGM-94 boiler at a variable feed water temperature (it was lowered from 230 to 170 ºС) while maintaining the flow of natural gas and maintaining steam production. They showed that in the first mode there is an increase in efficiency by 0.3%, but a decrease in the consumption of superheated steam by 47 t / h. While maintaining steam production, it is required to make an additional assessment of power increase from the burner devices and the temperature state of the heating surfaces. The latter is required due to a significant increase in the superheat temperature of both the superheated and secondary steam.

This article allows us to conclude that any changes in the regenerative heating circuit of a steam turbine installation require additional calculation of the steam boiler in order to verify its operability and efficiency in the new conditions.

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