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Development of a Mathematical Model for Obtaining Energy Characteristics of the Turbine Unit with the K-325-23.5 Steam Turbine

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Abstract

The results of mathematical modelling of the turbine unit with the K-325-23.5 steam turbine are presented. The mathematical model of the turbine is a system of equations for the components of the heat-balance diagram and the main dependencies of its operating characteristics obtained through the thermal full-scale tests. The developed mathematical model allows adjusting the results of the full-scale tests, creating normative characteristics and conducting research of the intermediate modes of the turbine operation. It is suggested to obtain correction curves for the main parameters of the turbine unit by conducting a simulation experiment on a mathematical model of the turbine instead of carrying out real tests. The correction is done by a complete recalculation of the turbine and its thermal cycle, taking into account the characteristics of the components of the turbine unit and the conditions of its operation during the test. As a result, the main energy characteristics under different operating conditions have been obtained, in particular, correction curves of the main steam consumption and specific heat consumption for the deviation of the initial steam parameters and changes in the heat-balance diagram were built.

Keywords: steam turbine; turbine unit; mathematical model; specific heat consumption; simulation experiment.

1. Introduction

The electricity market model operating currently in Ukraine can be briefly described as follows: the energy generating enterprises generate and supply the produced products to the wholesale market, from which it goes to end consumers through the energy supply companies. The energy generating enterprises include nuclear, thermal, hydraulic, solar and wind power plants, etc.

The essential feature of the wholesale market of Ukraine is that each power generating company has its own tariff for the purchase of electricity, which depends on the cost of its production. The lowest tariff is applied for nuclear (NPP) and hydraulic (HPP, PSP) power plants; a slightly higher tariff is used for thermal power plants (TPP) and the highest, the so-called "green tariff", is applied for enterprises that use renewable energy sources.

The cost of electricity generation at the TPP is almost 90% dependent on the amount and cost of the used fossil fuel. Therefore, in order to approve the tariff for each power plant or individual power unit, data on the use of fuel in the generation of electricity is required. Currently, the amount of data required for this is obtained experimentally, based on the results of which the energy characteristics of power generating equipment are built.

The primary focus in this paper is on the development of the mathematical model of the TPP turbine unit with the aim of its further use for creating the energy characteristics of the power generating equipment.

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2. Analysis of recent publications and research. Formulating the goal of the paper.

The energy characteristics of the power plant consist of the characteristics of the main equipment and data on the use of thermal and electrical energy for the own needs. The main indicator of the efficiency of conversion of the energy of the fuel burnt in the boiler unit into electrical energy is the energy conversion efficiency of the power unit, or the value of the specific reference fuel consumption for the production of a unit of output, gram of reference fuel/kW. Considering the turbine unit separately, the main energy characteristic for it will be the value of the specific consumption of thermal energy of steam per 1 kW of the generated electricity (kcal/kW) depending on the load of the power unit [1]. Currently, to obtain this value, several series of thermal testing of the turbine unit are conducted during its operation in various operating modes. At this stage, the first problem arises which consists in the fact that the test results are obtained when the equipment is operated in conditions different from the design (nominal) ones. It is also impossible to maintain the same operating conditions in different experiments during the tests. The second problem is that during the tests, it is impossible to cover all the operating modes of this turbine unit, and the characteristics must be determined for the maximum possible number of these modes and equipment operating conditions.

The first problem, i.e. bringing the test results to nominal conditions, is solved in practice in two ways. The first method consists in applying correction curves to the deviation of the actual conditions from the nominal ones during the experiment. This method is widely used in the international practice during the initial testing of turbines to confirm the manufacturers' guarantees [2], [3], [4]. The correction curves obtained by calculation are provided by a manufacturing plant. When testing the turbines in operation, the correction curves with typical energy characteristics are used. Such characteristics for the K-300-240 turbine are given as an example in [5]. However, this method of bringing the test results to nominal conditions by introducing individual corrections [6] has a number of disadvantages:

- a limited set of corrections that does not cover all the differences between the experimental conditions and the nominal ones;
- corrections are introduced by algebraic summation without taking into account the mutual influence of the parameter deviations;
- the corrections depend on the state of the turbine unit, i.e. applying the corrections, provided by the manufacturer for a new turbine, during the test of turbines with a long operating time is incorrect.

The second method of developing normative energy characteristics is to completely recalculate the cycle arrangement of the turbine unit for nominal parameters. This method is implemented on a personal computer by solving a system of equations describing the heat-balance diagram of the turbine unit. Such system of equations will be the basis of the mathematical model.

The second problem is solved by conducting a full-scale experiment on a real turbine unit or a simulation experiment on the mathematical model of this turbine unit [7], [8], [9].

The paper aims at developing a mathematical model and processing the data of thermal testing of a new turbine unit with the K-235-23.5 steam turbine of power unit No. 1 of Zaporizhzhia TPP in order to obtain the energy performance standards of the equipment. The available set of correction curves provided by the manufacturer does not cover all possible differences in the heat-balance diagram of the turbine unit and its operating conditions. The study of the turbine unit operation in unsteady conditions will be carried out using the developed mathematical model.

3. The development of a mathematical model of the turbine unit with the K-325-23.5 steam turbine

The thermal testing of the turbine unit with the K-325-23.5 steam turbine was carried out in the range of electrical load of the power unit from 50% to the nominal 325 MW, in accordance with the international standards [2], [3], [4]. The tests included the following series of experiments:

1) when working with a feed turbopump (FTP);
2) when working with a feed electric pump (FEP);
3) to determine the electrical power and specific heat consumption correction for turning off a group of high pressure heaters (HPH);

4) to determine the correction to the electrical power of the turbine unit for the change in the waste steam pressure [10].

The thermophysical properties of steam, water and condensate were determined using the mathematically described dependences on the pressure and temperature of the environment presented in [11].

According to the results of the thermal tests, the characteristics of the main elements of the turbine unit were obtained, including the internal relative efficiency η_{oi} of high (HPC), medium (MPC) and low pressure (LPC) cylinders, pressure loss in the steam pipelines of regenerative extractions, temperature differences of the low (LPH) and high (HPH) pressure heaters, the increase in the enthalpy of feed water in the feed pump, the energy conversion efficiency of the feed turbopump (FTP), etc. These characteristics are expressed through dependence diagrams that can be described using mathematical equations. The system of these equations constitutes the mathematical model of the turbine unit. The solution of this system of equations for any desired value is carried out by the method of successive approximations [12].

The recalculation of the heat-balance diagram of the turbine unit for the nominal operating conditions using a mathematical model can be carried out in two ways: with a constant steam flow rate and with a constant position of the steam distribution elements [13]. The first method has a significant drawback: upon the constant flow of main steam for the turbine, when converted to nominal parameters, the correction of the HPC energy conversion efficiency is required [6]. It is expedient, therefore, to use the second method for recalculating the heat-balance diagram, the position of the steam distribution elements remaining unchanged while maintaining the experimental value of the efficiency of the HPC. Under this condition, the main steam flow at nominal initial parameters is determined by the equation:

$$G_0 = G_0^{res} \cdot \sqrt{\left((P_0^n \cdot V_0)/(P_0 \cdot V_0^n)\right)}, \tag{1}$$

where G_0^{res} is the main steam flow under experimental conditions, t/h; P_0^n is HPC inlet nominal pressure of main steam, 240 kgf/cm^2; V_0 is the specific volume of main steam under experimental conditions, m^3/kg; P_0 is HPC inlet test pressure of main steam, kgf/cm^2; V_0^n is the specific volume of main steam under nominal conditions, 0.01336 m^3/kg.

The total heat consumption for the turbine under nominal conditions Q_0, Gcal/h, is determined by the equation:

$$Q_0 = \left(G_0 \cdot \left(i_0^n - i_{gw}^n\right) + G_{cpp}^n \cdot \left(i_{hpp}^n - i_{cpp}^n\right)\right)/10^3, \tag{2}$$

where i_0^n = 793.7 kcal/kg is the enthalpy of main steam before HPC at nominal initial parameters; i_{gw}^n is the enthalpy of feed water after HTP and recalculation of heat-balance diagram for nominal conditions, kcal/kg; G_{cpp}^n is the flow of cold reheat steam under nominal conditions, t/h; i_{hpp}^n is the enthalpy of hot reheat steam at a temperature of 540 °C and pressure obtained after recalculating the heat-balance diagram for nominal conditions, kcal/kg; i_{cpp}^n is the enthalpy of cold reheat steam under nominal conditions, kcal/kg.

The power of the turbine under nominal conditions, MW, is determined by the equation:

$$N_t^n = N_t^D + \Delta N_{\cos(\varphi)} + \Delta N_{pk} + \Delta N_{sch}, \tag{3}$$

where N_t^D is the electric power at the terminals of the generator under experimental conditions, MW; $\Delta N_{\cos(\varphi)}$ is the correction for the deviation of the generator power factor from the nominal one, MW; ΔN_{pk} correction for the deviation of the waste steam pressure in the experimental conditions from the nominal one, MW; ΔN_{sch} is the total correction for differences of the heat-balance diagram and parameters under experimental conditions from the nominal conditions (except for the waste steam pressure in the condenser and the generator power factor) and the change in the main steam flow for the turbine during the transition to nominal conditions, MW.

The correction ΔN_{sch} is equal to the difference of the turbine's internal capacity in nominal and experimental conditions and is obtained based on the results of recalculating the heat-balance diagram of the turbine unit for nominal conditions using a mathematical model.

The specific gross heat consumption for the turbine in nominal conditions q_t^n, kcal/(kW·h), when working with the FTP, is determined by the equation:

$$q_t^n = \frac{Q_0}{N_t^n + N_{gtp}} \cdot 10^3, \tag{4}$$

where N_{gtp} is the power of the feed turbopump, MW.

Using the characteristics of the main elements of the turbine unit and equations 1, 2, 3, 4, the main energy characteristic is obtained, i.e. the dependence of the total and specific heat consumption on the electrical output when working with the FTP under nominal conditions (Fig. 1).

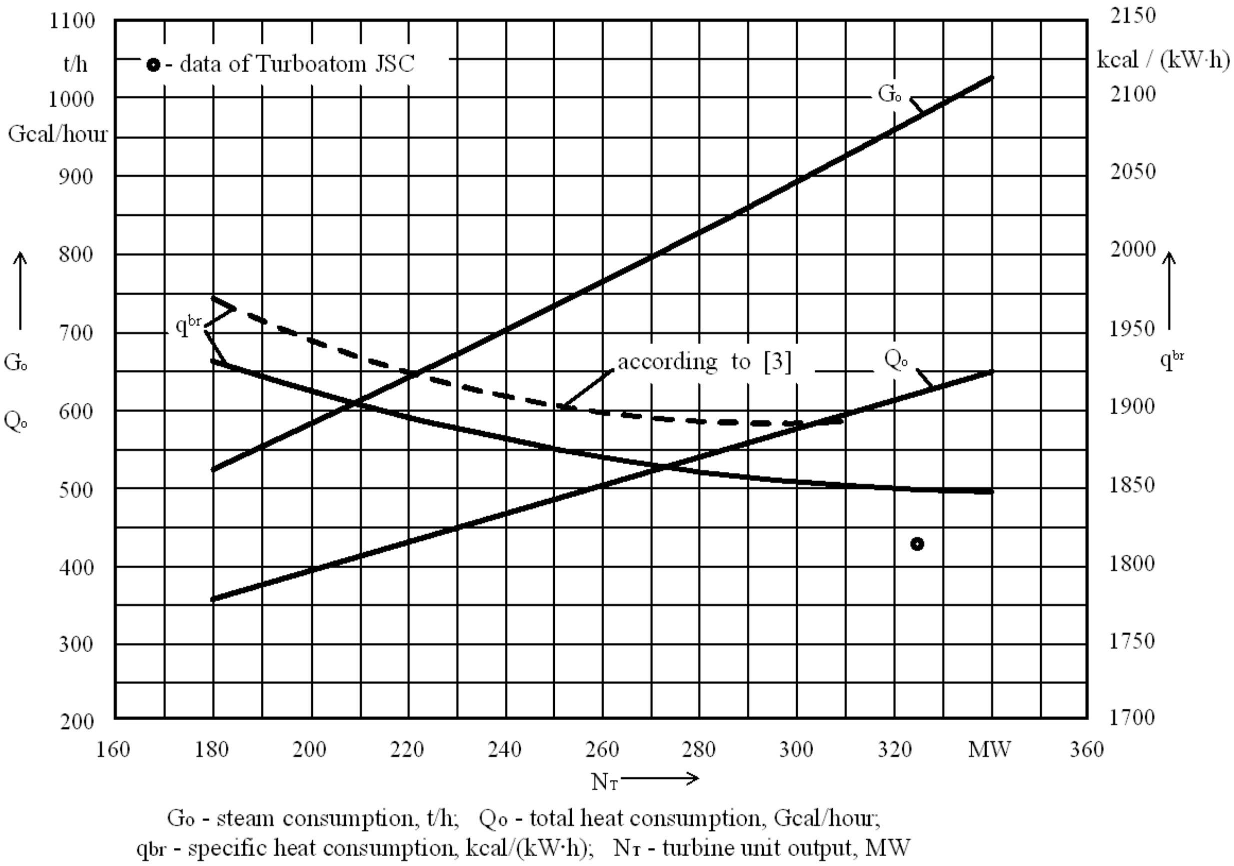

Fig.1. Main steam consumption, total and specific heat consumption for the K-325-23.5 turbine, depending on the electric output when working with FTP under nominal conditions.

As can be seen from Fig. 1, the line of dependence of the specific steam consumption for the K-325-23.5 turbine (solid line) lies below the dependence line for the K-300-240 turbine (dashed line), in place of which it was installed. A new turbine K-325-23.5 is 2% more efficient in converting the kinetic energy of the steam into mechanical energy of its shaft rotation compared to the turbine K-300-240 at the time of its installation.

4. Simulation experiment on a mathematical model of the turbine unit

The main energy characteristic in Fig. 1 is obtained by recalculation on the mathematical model during operation in nominal conditions. The following is taken as nominal operating conditions:

- design heat-balance diagram of the turbine unit;
- main steam pressure before the turbine of 240 kgf/cm^2;
- temperature of main steam and hot reheat of 540 °C;
- waste steam pressure in the condenser of 0.372 kgf/cm^2;

- injection of feed water into reheat of 0 t/h;
- pressure in the deaerator of 7 kgf/cm^2;
- pressure drop at the boiler feed valve of 20 kgf/cm^2.

During the operation, the turbine unit does not operate under nominal conditions, since one or more parameters of the working fluid or heat-balance diagram will always deviate. Therefore, it is necessary to develop additional characteristics for the possibility of normalization of such unsteady conditions. That is, it is necessary to develop corrections to the specific heat consumption for the turbine and consumption of main steam or electrical power.

The corrections are calculated by conducting a simulation experiment on the mathematical model of the turbine unit [14]. To calculate the corrections, it is necessary to change the parameter for which the correction must be determined. As a result of the recalculation, the new values of the desired parameter in the changed conditions and its deviation from the nominal values, i.e. corrections, are obtained. This operation is repeated for different turbine power values.

The calculations result in the correction curves for the deviation of the initial steam parameters from the nominal ones, determined at different values of the turbine power. That is what qualitatively distinguishes the corrections determined using the mathematical model from the corrections of the manufacturing plant that are calculated only for the operating mode at the rated power capacity. The correction curves provided by the manufacturer are shown in Fig. 2 as an example.

The correction curves of the main steam consumption, total and specific heat consumption for the turbine for the deviation of the main steam pressure, main steam temperature and hot reheat from the nominal ones, obtained by a simulation experiment on the mathematical model of the K-325-23.5 turbine unit, are shown in Fig. 3.

As can be seen from Fig. 3a, the correction curves for the deviation of the main steam pressure to the main steam consumption and the total and specific heat consumption for the turbine change their nature depending on the power of the turbine. That is, the correction can be with a negative sign at one power value and with a plus sign at another power value, this correction being for the same pressure deviation value. This is due to the fact that the same value of the deviation of the main steam pressure from the nominal value at different values of the turbine power has a different effect on its efficiency and, accordingly, on the consumption of main steam.

In addition to the corrections for the deviation of the initial parameters of the steam from the nominal ones, using the mathematical model of the turbine unit, it is possible to calculate the corrections for changes in its heat-balance diagram from the design one or deviations of the operating mode from the nominal conditions. For example, one can determine the correction for adding the feed water injection into the reheat steam path. Such correction is determined similarly to the above corrections for the deviation of the initial steam parameters. Under nominal conditions, there is no injection of feed water into the steam reheat path. To calculate the correction, the injection value is set at, for example, 20, 40, 60 t/h and the system of equations is solved at some constant value of the turbine power. As a result of the solution, we obtain the value of the main steam consumption for the turbine and the value of the total and specific heat consumption. These values are compared with the values under nominal conditions at a given turbine power and thus we obtain corrections to the main steam consumption, total and specific heat consumption for the turbine for the given amount of feed water injection. By repeating this operation for several turbine power values, the correction curves shown in Fig. 4 are obtained.

5. Analysis of the results of the simulation experiment on the mathematical model

With the help of the mathematical model of the turbine unit, it is possible to solve the above-mentioned problems faced by debugging organizations that conduct tests and develop regulatory energy characteristics of power units of thermal power plants. A complete recalculation of the heat-balance diagram of the turbine unit on a mathematical model makes it possible to bring the results of thermal testing to nominal conditions with higher accuracy than with the help of factory corrections [14]. This allows taking into account the influence of differences in all parameters that took place during the full-scale experiment in their mutual influence.

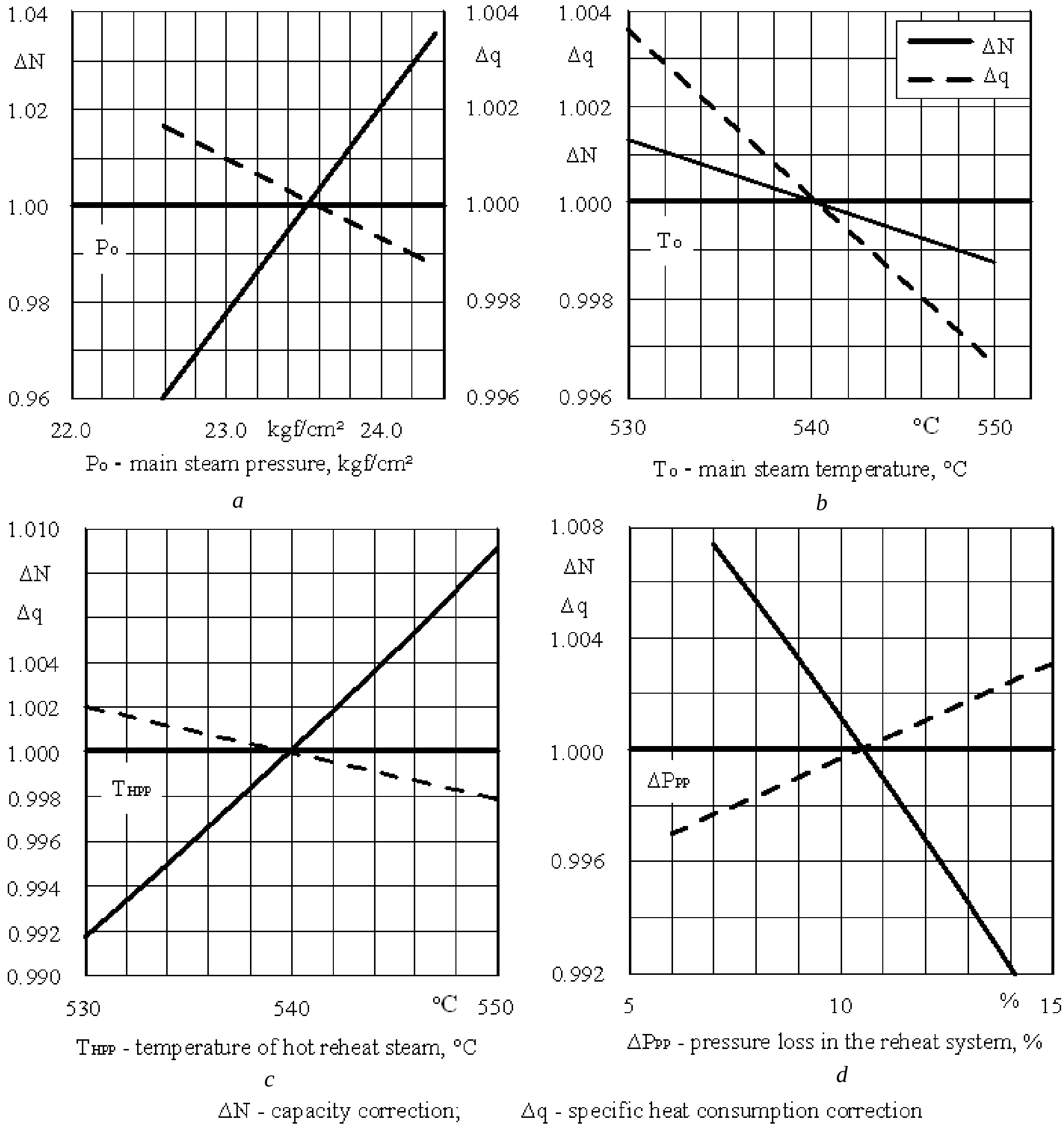

Fig. 2. Correction curves for changes in power and specific heat consumption upon changes in: *a* – main steam pressure; *b* – main steam temperatures; *c* – temperature of hot reheat; *d* – pressure loss in the reheat system.

It is worth noting that with the help of a mathematical model it is possible to calculate the characteristics of the equipment in any unsteady conditions of operation, i.e. to take into account the deviation of any technological parameter from the nominal one or any change in the heat-balance diagram of the turbine unit from the design one. In order to do that, it is not necessary to conduct additional full-scale tests on the existing equipment, which will significantly save time and labour costs.

Comparing the correction curves provided by the manufacturing plant (Fig. 2) and those obtained by the simulation experiment (Fig. 3 and 4), it can be observed that these curves have different nature. This is due to the fact that factory corrections are calculated at the rated electric power in a narrow range of parameter changes. Using the developed mathematical model, corrections can be calculated in a wide range and for different values of the capacity of the power unit.

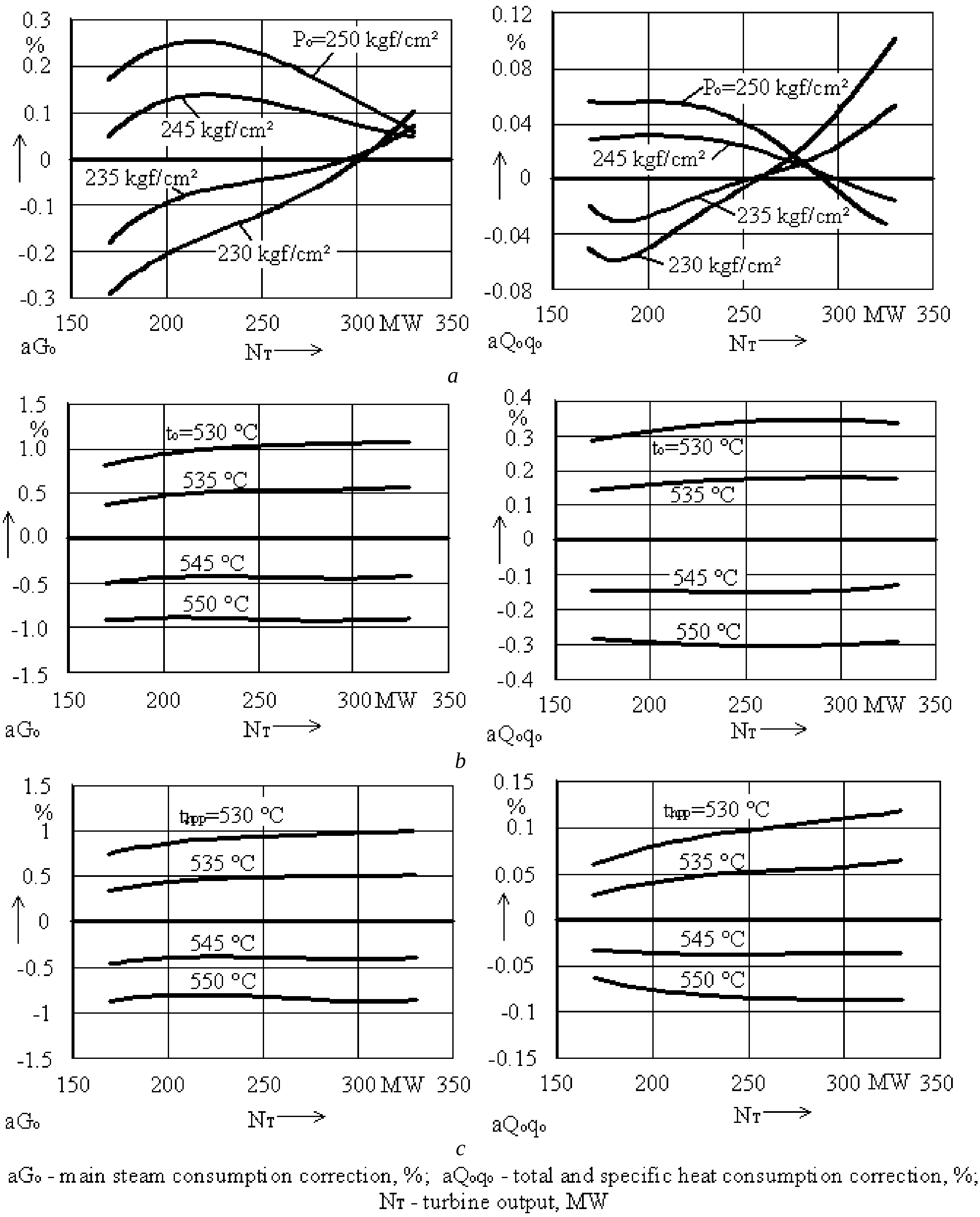

Fig. 3. Correction curves for main steam consumption, total and specific heat consumption for deviation from nominal values of: *a* – main steam pressure; *b* – main steam temperatures; *c* – hot reheat steam temperature.

The mathematical model also allows calculating the corrections for the change of the balance-heat diagram of the turbine unit from the design one, for example, for switching the power supply of the deaerator with the steam of different extraction, for turning off any heater, or injecting the feed water into the steam reheat path.

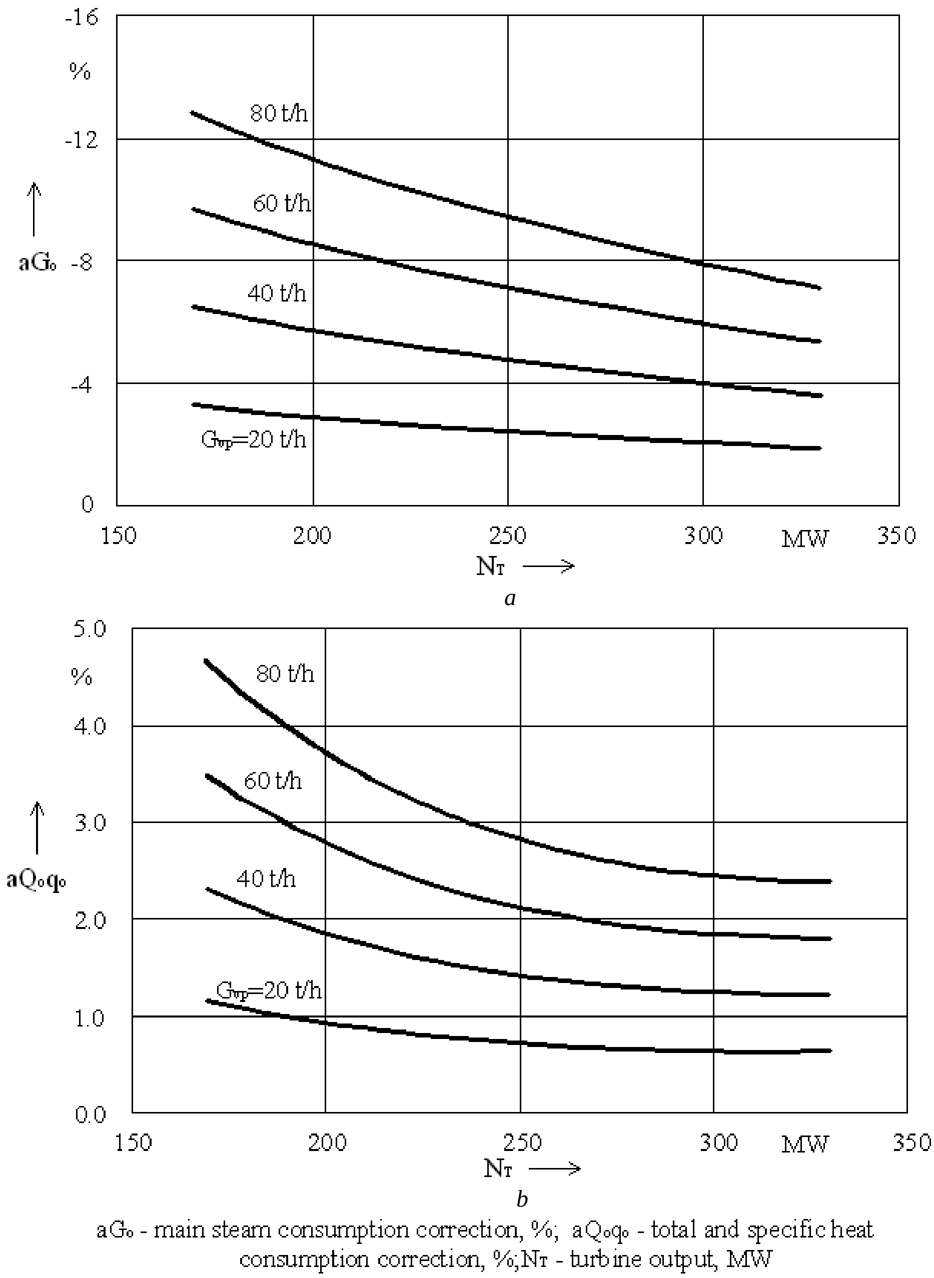

Fig. 4. Correction curves for adding of the feed water injection into the steam reheat path up to: *a* – main steam consumption for the turbine; *b* – total and specific heat consumption.

An example of correction curves for adding the injection is shown in Fig. 4. The correction curves in this figure are calculated at different values of feed water consumption depending on the electrical capacity of the power unit.

6. Conclusion

According to the results of the thermal testing of the new K-325-23.5 steam turbine of the power unit No. 1 of Zaporizhzhia TPP, a mathematical model of the turbine unit was developed. Using the model, the test results were recalculated from the experimental conditions to the nominal conditions, followed by building the energy characteristics of the turbine. The mathematical model was also used for calculating the correction factors for the deviation of the main parameters of the working fluid from the nominal ones, as well as for the differences in the heat-balance diagram from the design one.

The correction curves for the main steam consumption, the total and specific heat consumption for the pressure deviation and the temperature of the HPC inlet main steam, the temperature of the HPC inlet reheat steam and the feed water injection into the intermediate pressure path were calculated and constructed for different values of electric load of the power unit.

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Розробка математичної моделі для одержання енергетичних характеристик турбоустановки з паровою турбіною К-325-23,5

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Анотація

Представлені результати математичного моделювання турбоустановки з паровою турбіною К-325-23,5. Математична модель турбіни являє собою систему рівнянь елементів теплової схеми та основних залежностей її робочих характеристик, які були отримані завдяки тепловим натурним випробуванням. Розроблена математична модель дозволяє коректувати результати натурних випробувань, будувати нормативні характеристики, а також проводити дослідження проміжних режимів роботи турбіни. У статті запропоновано отримувати коригувальні криві основних параметрів турбоустановки шляхом проведення імітаційного експерименту на математичній моделі турбіни замість проведення реальних випробувань. Коректування здійснюється шляхом повного перерахунку турбіни та її теплового циклу з врахуванням характеристик компонентів турбоустановки та умов її експлуатації під час випробування. В результаті роботи отримано основні енергетичні характеристики в різних умовах експлуатації, зокрема побудовані поправочні криві до витрати свіжої пари та питомої витрати теплоти на відхилення початкових параметрів пари та зміни у тепловій схемі.

Ключові слова: парова турбіна; турбоустановка; математична модель; питома витрата теплоти; імітаційний експеримент.