It is shown that the technical condition of condensing devices of steam turbines largely determines the amount of electricity losses, reliable and economical operation of NPP units. Analysis of the heat transfer process in the condenser showed that the main causes of load reduction are determined by rising cooling water temperature and deviation of steam pressure from normal value. It is shown that among diagnostic parameters except leakage volumes there must be an assessment of contamination of the heat transfer surface which significantly affects the reduction of electricity generation.

The modernization main points of the condenser of the Zaporizhzhya NPP power unit No. 3 on the principle of «block-modular» design developed by PJSC «Turboatom» and the characteristics of the condenser provided by the new design are considered.

To reflect the real mode of operation of the condensing unit, it is proposed to model the contamination of the heat exchange surface and the presence of leakages in the condenser space using the method of thermal calculation of the condenser by iterative methods. It was found that reducing the increase in electricity generation as a result of the effects of the study factors can partially or even completely absorb the effect of upgrading the condenser plant. It will provide a significant increase in electricity generation with relatively low capital investment compared to construction of new NPP power units and improve the accuracy of power generation forecasts

Keywords: thermal calculation of NPP condenser, air leakage, contamination, increase of electric power

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DETERMINATION OF THE ELECTRICAL POWER INCREASE AT THE GENERATOR TERMINALS OF A NUCLEAR POWER PLANT UNIT AT DIFFERENT CONDENSER STATES

Kateryna Bratkovska
Corresponding author
PhD, Associate Professor*
E-mail: bratkovskaja@gmail.com

Yuliya Liush
PhD, Associate Professor*

*Department of Power Supply for Industrial Enterprises
Zaporizhzhia Polytechnic National University
Zhukovskoho str., 64, Zaporizhzhia, Ukraine, 69063

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1. Introduction

The condensing unit is designed to reduce steam parameters downstream of the turbine, which is one of the main methods of achieving a high thermal efficiency of the steam-turbine plant. It is known that when the pressure downstream the turbine changes by 1 kPa, the efficiency of steam-turbine plants of nuclear power plants (NPP) varies by about 1.5–2 % [1]. Thus, the technical condition of condensation devices of steam-turbine plants significantly affects the efficiency of electricity generation and the reliability of NPP power units.

The decrease in power generation occurs both due to the softening vacuum in the condensers and due to the discharge of power units for searching of water leakage. Specialists of the South Ukrainian NPP assess the undersupply of electricity into the network due to contamination of condensers at the idle level of the power unit for half a day or a day [2].

The modernization of the existing equipment of NPP power units is necessary to ensure the energy safety of any country, the implementation of its Energy Strategy, and also makes it possible to work the NPP equipment together with the energy systems of other countries. Thus, the modernization of steam-turbine condensers can provide a significant increase in electric energy generation with relatively low capital investments compared to the costs of building new NPP power units.

2. Literature review and problem statement

Work [3] explains the role played by the condenser and describes some damage mechanisms that affect the whole condenser unit. These mechanisms will continue to cause leakage until the main causes of malfunctions are identified and changes are made to materials, water treatment or operation of the plants to eliminate them.

In the work [4] means of intensification of heat exchange in equipment of nuclear power plants are considered. In particular, various types of ribs have analyzed and design recommendations have made to determine the intensity of heat release from promising types of heat exchange surfaces. However, the authors do not consider the aspect of increasing electrical power either when changing the operation of installations to prevent leakage [3], or when intensifying heat transfer [4].

Various approaches to optimizing condensers at the design stage are also known. Work [5] is present an iterative "speed search algorithm" that focuses on finding the correct tertiary coolant rate instead of the total heat transfer coefficient for designing a condenser of a large 1200 MW nuclear power plant. The limitation of the results application is the taken into account average range of water temperatures in the reservoir of the tropical region 28–32 °C during the summer.

The work [6] shows the principles and results of modernization of condensers of steam-turbine units of power unit

No. 3 of Zaporizhzhya NPP according to the principle of “block-modular” execution. The unique design of condensers provides an increase in the thermal power of the reactor plant of generating units up to 107 %. However, the characteristics of the increase in electric power at the terminals of the generator with the new “block-modular” condensers depending on the state of the condenser are not disclosed.

In work [7] increase of NPP generation power is investigated. It is shown that it requires an increase in cooling water or a decrease in water temperature. This in turn will require an increase in the capacity of the water circulation pump or the scale of the cooling tower, which will lead to a significant increase in investment.

It is known that the NPP power unit equipment resource is controlled using an integrated diagnostic system. In work [8] it is noted that such system is both a tool for determining the technical condition and a method of integrated engineering survey of equipment and evaluation of its residual resource.

The nuclear power plant condenser control system consists of a pressure monitoring system, a condensate water cooling degree control system and a water level control system. [9] presents a condenser control optimization method based on a multipurpose optimization algorithm. This method allows to obtain high-quality control parameters, but does not allow to evaluate the state of the condenser and its effect on the generation of electricity.

The work [10] considers the principles of thermoeconomic diagnostics, the purpose of which is to identify the causes of abnormal operation of the energy transportation system. The continuation of this study is the work [11], which shows the feasibility of comparing two modes of operation of the plant: design (reference) and real. In the last mode there are anomalies in the operation of the elements, caused by the appearance of additional irreversibility during their operation.

This approach used in the work [12], according to which the basis of thermoeconomic diagnostic is a decomposition cost analysis of the destruction of exergy in the elements of the system. At the same time analysis of perfection of heat transfer process in condenser is carried out by means of coefficient of losses of product exergy. In work [13], a similar analysis is carried out to determine the number of units of exergy destruction. Work [14] uses the element thermodynamic efficiency improvement potential indicator (Van Goole index) for this purpose. However, it is advisable to evaluate the perfection of the heat transfer process in the condenser by the indicator of the final result of the process. For NPP generating units, this indicator is the volume of electricity generation.

Work [15] considers the issue of renovation of NPP generating units by introducing automatic diagnostics of low-potential complexes (LPC) of turbine equipment. The author emphasizes that the main reasons for the load reduction are determined by the operating conditions of the LPC – an increase in the temperature of the cooling water and a deviation of the steam pressure in the condenser from the normal value. It is shown that among the diagnostic parameters there is a value of suction leakages, however, there is no assessment of contamination of the heat exchange surface.

All this allows us to argue that it is advisable to conduct a study on determining the connection between the appearance of air leakages in the condenser, the appearance of contaminants in the heat exchange surface and the increase in the electric power of the turbine plant. This takes into account the deepening of the assumed pressure of the steam owing to the modernization of the condensers.

3. The aim and objectives of the study

The purpose of the study is to determine the change in the electric power of the turbine plant at the terminals of the generating unit of the nuclear power plant when air leakges and contaminants of the heat exchange surface appear on the basis of statistical data. This will make it possible to more reasonably use the results of diagnostics and monitoring of the technical condition of the modernized model of the condenser of the block-modular design. In particular, the accuracy of the forecast of electricity generation volumes can be increased and the number and periodicity of routine maintenance and overhaul repairs can be changed.

To achieve the goal, the following objectives were set:

– analyze the mode characteristics of the “block-modular” condenser taking into account the increase in electric power of the turbine plant on the generator terminals;

– define equations describing the dependence of the electric power of the turbine plant on the change in steam flow rate in the condenser and the appearance of surface contaminants;

– analyze the regression equation parameters of the power gain on the generator terminals.

4. The study materials and methods

The main characteristic of the operation of the condenser is the value of the underpressure or absolute pressure created by it in the condenser. In addition, when calculating the heat transfer coefficient in the condenser according to various methods, it is necessary to know the average temperature of the cooling water. Based on these data, the heat transfer coefficient from the water side is calculated. Based on the temperature difference between steam and water, the heat transfer coefficient from the steam side is calculated. All these temperatures are determined by thermal calculation. This requires iterative methods, when pre-set and then refined some necessary values for calculation (e.g. final cooling water temperature). The calculation was performed according to the method described in [1].

Heat transfer coefficient with sufficient accuracy for engineering calculations of condensers can be determined by formula (1):

$$K = 4{,}070 \cdot a \cdot \left(\frac{1.1 \cdot w_w}{d_{in}^{0.25}} \right)^{0.12 a (1 + 0.15 t_{1w})} \times$$
$$\times \left[1 - \frac{\left(0.52 - 0.0072 \cdot d_k\right) \cdot \sqrt{a}}{1{,}000} \cdot \left(35 - t_{1w}\right)^2 \right] \times$$
$$\times \left[1 + \frac{z-2}{10} \cdot \left(1 - \frac{t_{1w}}{35} \right) \right] \cdot \Phi_d; \quad (1)$$

where a is the coefficient of the state of the heat transfer surface of the condenser (takes into account the contamination of the tubes, and also indirectly reflects the density of the vacuum system);

w_w is the speed of cooling water in the tubes, m/s;

d_{in} is the inner diameter of the tubes, mm;

t_{1w} is the temperature of the cooling water at the inlet to the condenser, °C;

z is the number of water strokes in the condenser;

d_k is the specific steam load of the condenser, g/(m^2·s);

Φ_d is the coefficient that takes into account the influence of the steam load of the condenser (d_k).

In the first approximation, the water temperature at the outlet of t_{2w} was determined at the latent heat of the phase transition $r=\Delta h_k$=2,435.94 kJ/kg:

$$t_{2w}=t_{1w}+\frac{D_k\cdot\Delta h_k}{G_w\cdot c_w};\qquad(2)$$

where G_w is the flow of cooling water through the condenser; c_w is the heat capacity of water at constant pressure, kJ/(kg·K).

Underheating of water to saturation temperature:

$$\delta_t=\frac{t_{2w}-t_{1w}}{e^{\frac{K\cdot F}{G_w\cdot c_w}}-1};\qquad(3)$$

where K is the heat transfer coefficient in the condenser, W/(m^2·K).

Steam saturation temperature in the condenser:

$$t_s=t_{1w}+\Delta t+\delta_t,\qquad(4)$$

where Δt is the heating of the cooling water in the condenser, K.

From the value of the last temperature, the latent heat of the phase transition is determined and the value of the water temperature at the outlet of the condenser is refined.

According to the calculation method, the difference between the received and the obtained water heating values is determined. Then, if it is necessary to continue the calculation in the second approximation, the underheating of water to the saturation temperature and the saturation temperature of steam in the condenser are calculated in the same way.

The pressure in the condenser, which corresponds to the saturation temperature t_s, is found in the water vapor property tables as a function of the saturated steam temperature. Further, based on the typical energy characteristic of the turbine or on the universal dependence $\Delta N/D_{k=f}(p_k/D_k)$, the increase in electric power on the generator terminals is determined.

Presence of air leakages in condenser space in calculation is modeled by change of steam flow rate in condenser.

The specific steam load was determined by the formula:

$$d_k=D_{k/}F,\qquad(5)$$

where D_k is the steam flow rate, t/h; F is the cooling surface of the condenser, m^2; at the nominal value of the specific steam load d_{nomk}=40.30 kg/(m^2·h).

Maximum steam load:

$$d_{\max k}=(0.9-0.012\cdot t_{1w})\cdot d_{nomk};\qquad(6)$$

steam load factor in the range $d_k<d_{\max k}$:

$$\Phi_{d=dk}/d_{\max k}\ (2-d_k/d_{\max k}).\qquad(7)$$

Total thermal resistance to heat transfer in condenser with clean heat exchange surface is equal to sum of thermal resistances on side of cooling water, wall of tubes of heat exchange surface and on side of condensed steam. These thermal resistances are introduced into the formula (8) as terms in the denominator of the expression.

$$K=\frac{1}{R_w+R_{wt}+R_{st}};\qquad(8)$$

where R_w, R_{wt}, R_{st} are the thermal resistances on side of cooling water, wall of tubes of heat exchange surface and on side of condensed steam, respectively, m^2·K/W.

$$R_w=\frac{1}{\alpha_w}\cdot\frac{d_{out}}{d_{in}};\qquad(9)$$

where α_w is the heat transfer coefficient from the wall of the tube to the water, W/(m^2·K); d_{out}, d_{in} are the diameters of the outer and inner tube, respectively, m.

$$R_{wt}=1.15\cdot\frac{d_{out}}{\lambda_{wt}}\cdot\lg\frac{d_{out}}{d_{in}};\qquad(10)$$

where λ_{wt} is the thermal conductivity of the tube wall material, W/(m·K).

$$R_{st}=\frac{1}{\alpha_{st}};\qquad(11)$$

where α_{st} is the heat transfer coefficient from the steam to the wall of the tube, W/(m^2·K);

In the presence of contaminants of the heat exchange surface, their thermal resistance is introduced by an additional term into the denominator of the expression, that is,

$$K_c=\frac{1}{\frac{1}{K}+R_c}.\qquad(12)$$

where R_c is the thermal resistance of contamination, m^2·K/W.

The above-described method of thermal calculation of the condenser to reflect the actual operation of the plant allows simulating contamination of the heat exchange surface and the presence of air leakages in the condenser space. The first is taken into account by thermal resistance with thermal conductivity coefficient 2 W/(m^2·K) at the analysed thickness of 0–0.2 mm, and the second – by changing the steam flow rate in the condenser.

5. Results of electric power investigation at generator terminals at different condenser states

5. 1. Analysis of changes in characteristics of the "block-modular" condenser

After long-term operation, defects in the turbine condensers begin to show, it is leading to leakages of cooling water and tend to grow gradually. The most likely causes of this type of defects are: corrosion cracking of metal in places of local mechanical action; development of pitting-ulcer defect or application of loads in places of forge-rolling joints; mechanical damages of pipes. The organization of salt compartments in the condenser housing can serve as an operational detection of these leakages. An effective method of reducing the leakage is, for example, to provide double tube boards with condensate supply with a pressure exceeding the pressure of cooling water in the cavity between them.

Power unit No. 3 of the Zaporizhzhya NPP was launched in 1986. It consists of a K-1000-60/1500-2 turbine, which, before the extension of the life cycle of the unit and the modernization, was equipped with three condensers of type K-33160 and 12th intake and discharge devices. The proposed "block-modular" design of the new generation condenser provides increased reliability, operability and safety and increases the service life cylce of the entire unit. The author's developments of PJSC "Turboatom" have used in created design of the condenser K-38080 [6].

The design of the condenser, made with a "modular" arrangement of the pipe bundle, prevents subcooling of the condensate and saturation of it with non-condensable gases. The result is tightness, and air leakages and the ingress of cooling water into the steam space are excluded. The maximum value of possible leakage of cooling water into the steam space of the condenser is not more than 0.00001 % of the steam flow rate to the condenser during the entire life cycle of the condenser. In the design of the lower modules, additional elements are provided (deaeration panels and deaeration devices) that allow reducing the oxygen component in the condensate.

Thus, the new condenser design provides [6]:

– installation of housings on existing foundation supports without changing the structure of the foundation and its calculation;

– tightness of cooling pipes attachment in external boards due to forge-rolling and welding according to the manufacturer's technology;

– deepening of design steam pressure in condenser (vacuum) with corresponding increase of turbine plant electric power on generator terminals;

– installation of manholes on the inlet, outlet and intermediate chambers, which provide access to cooling pipes to determine possible defects of pipes and control the density of connection of cooling pipes with external boards;

– coating of internal surfaces of water chambers, covers and anchor joints with anticorrosive material;

– removal of steam-air mixture, which has not condensed, from the tube bundle;

– complete condensation of steam coming from turbine low-pressure cylinders;

– operability at forcing of reactor plant thermal power up to 3210 MW (107 %).

The characteristics of the condenser after modernization are shown in Table 1.

Increasing the cooling surface of the condenser made it possible to achieve a decrease in steam pressure by 7 %, cooling water flow rate by 1 %, cooling water velocity in pipes by 5 %.

Table 1

Design characteristics of condenser K-38080 according to [6]

Indicator	After modernization
The type	superficial
Cooling surface, m^2	38080
Pipe type	welded
Assortment of pipes, mm	Ø23×0.5×14060 Ø23×1.0×14060
Number of pipes	37644
Fastening of pipes in boards of external	rolling and welding
Number of moves/streams	2/2
Steam flow rate in a condenser, t/h	1114.22
Vapor pressure in the condenser, kPa	3.57
Consumption of cooling water in the condenser, t/h	56000
Estimated cooling water temperature, °C	15
Water velocity in the pipes, m/s	2.0

5. 2. Defining of dependence of electric power of turbine plant on change of steam flow rate in condenser and occurrence of surface contaminants

According to the mode characteristics of the condenser given in Table 2, the increase of electric power on the generator terminals is calculated and pointed out in Fig. 1, 2 when the steam load factor changes (Fig. 1) and the contamination thickness changes (Fig. 2).

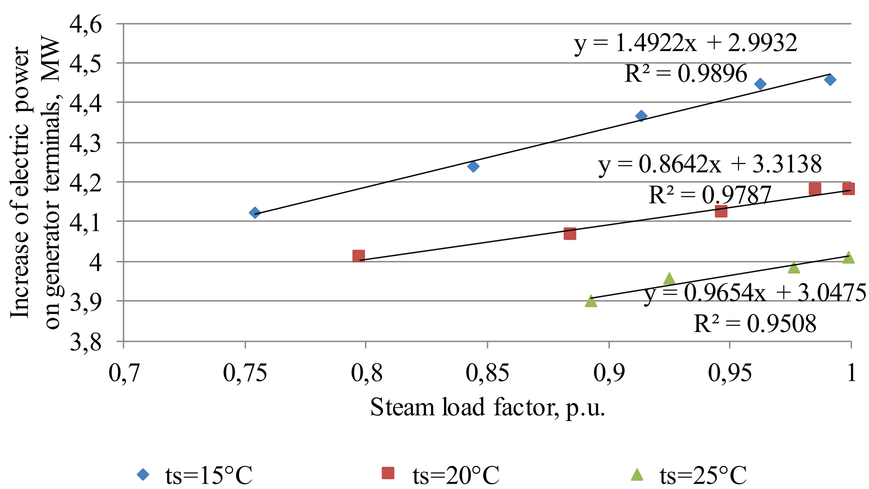

Fig. 1. Increase of electric power at generator terminals at change of steam load factor

Table 2

Mode characteristics of the condenser before and after modernization according to [6]

Estimated cooling water temperature at the inlet to the first condenser housing, °C	Average value of condenser vapor pressure, kPa		Increase of electric power of the turbine unit on generator terminals after condenser modernization, MW
	existing K-33160	modernized K-38080	
15	3.825	3.57	0.9
20	4.923	4.668	2.1
25	6.414	6.1	3.1
30	8.345	7.963	4.1
35	10.846	10.356	5.2

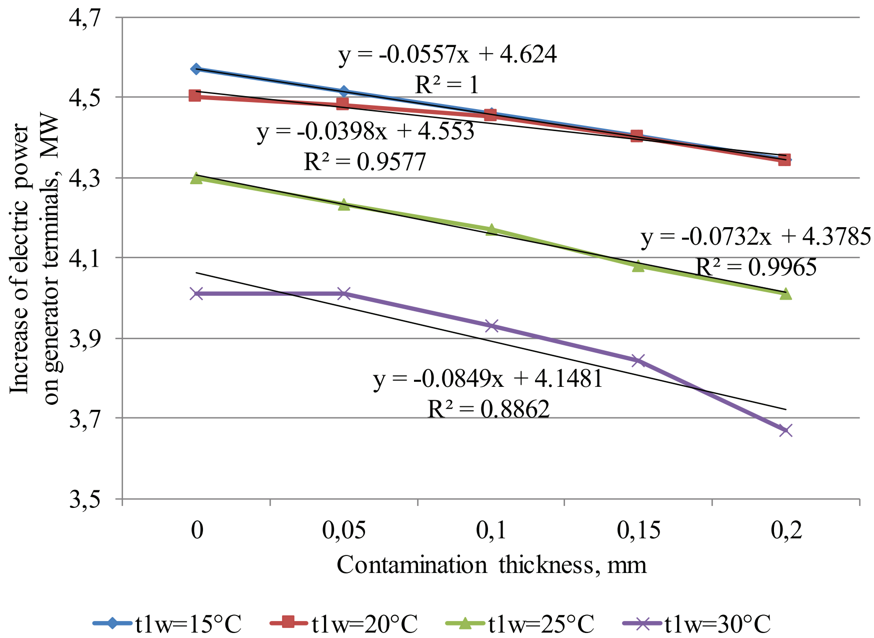

Fig. 2. Increase of electric power at generator terminals at change of contamination thickness

Analysis of the defined dependencies showed that when the steam load factor decreases, the increase in electric power at the generator terminals decreases. The occurrence of contaminants on the heat exchange surface also negatively affects the increase in electric power at the generator terminals. At the same time, the temperature of the cooling water also affects the change in the investigated parameter: the higher the temperature, the lower the effect of modernization of the condenser.

The dependence of the electric power of the turbine plant on the change in the steam flow rate in the condenser and the appearance of contaminants in the heat exchange surface can be investigated by constructing a multiple linear regression dependence based on statistical data.

To simplify the further presentation of materials, a notation has been introduced:

– Y is the predicted increase of electric power at generator terminals,

– X_1 is the inlet water temperature, °C,

– X_2 is the steam load factor, p.u.,

– X_3 is the contamination thickness, mm.

Given the conditions for defining a multifactor model for the absence of multicollinearity of factors, the nature of the interrelation of the dependent variable Y from the independent variables X_{1i}, X_{2i}, X_{3i} is estimated. To do this, a matrix of paired correlation coefficients was constructed (Table 3).

Table 3

Matrix of paired correlation coefficients

	Y	X_1	X_2	X_3
Y	1	–0.772534862	0.205126	–0.09474
X_1	–	1	0.2905	0.182112
X_2	–	–	1	0.429806
X_3	–	–	–	1

The paired correlation coefficients between independent model variables are insignificant. This indicates the absence of multicollinearity. So, in this case, it is advisable to define a model of multiple linear regression using the least squares method. Table 4, 5 shows the results of the analysis.

Table 4

Regression statistics

Multiple R	0.905222
R-square	0.819427
Normalized R-square	0.80137
Standard error	0.102024
Observation	34

From the Table 4 the coefficients of the regression equation obtained:

b_0=3.20628, b_1=–0.03906,

b_2=1.918999, b_3=–0.49651.

Respectively,

$$\hat{Y}_i=3.20628-0.03906\,X_{1i}+ +1.918999X_{2i}-0.49651X_{3i}, \quad (13)$$

Y is the predicted increase of electric power at generator terminals; X_1 is the inlet water temperature, °C; X_2 is the steam load factor, p.u.; X_3 is the contamination thickness, mm.

Table 5

Results of multiple regression analysis

	Coefficients	Standard error	t-statistics	P-Value
Y-section	3.20628	0.291717	10.99108	4.84E-12
$X_{1i}=t_{1w}$	–0.03906	0.003532	–11.0603	4.16E-12
$X_{2i}=\Phi_d$	1.918988	0.317102	6.051634	1.21E-06
$X_{3i}=\sigma$	–0.49651	0.265186	–1.87229	0.070943

5. 3. Analysis of parameters of regression equation of electric power gain on generator terminals

The estimate of parameter b_0 is equal to 3.20628 and is an estimate of the average increase in electric power at the generator terminals, MW, in the absence of the influence of water temperature at the inlet, steam load factor, contamination thickness. That is, this value characterizes the increase due to the modernization of the condenser.

The estimate of parameter b_1 is –0.03906. This means that with a given steam load factor and contamination thickness the increase in inlet temperature will lead to a reduce in the expected increase in electric power at the generator terminals by 40 kW. The estimate of parameter b_2 is 1.918988. This means that at fixed inlet water temperatures and contamination thickness the steam load factor growth is accompanied by a grow in the expected increase in electrical power at the generator terminals by 1.92 MW. In turn, the estimate of parameter b_3 is –0.49651. That is, at fixed inlet water temperature and the steam load factor, the increase in contamination thickness is accompanied by a reduce in the expected increase in electric power at the generator terminals by 0.5 MW. These estimates make it possible to better understand the effect of the investigated factors on the change in electric power at the generator terminals.

Since there are at least three explanatory variables in the multiple regression model, the multiple mixed correlation coefficient is a fraction of the variable Y variation, which is explained by a given set of explanatory variables:

$$r^2 = 0.8194.$$

This means that 81.94 % of the increase in electrical power at the generator terminals is due to changes in inlet water temperature, steam load factor and contamination thickness.

The analysis of the distribution of residues depending on the predicted values is given in Fig. 3. The amount of residues takes on both positive and negative values. Therefore, the condition of linear dependence of variable Y on explanatory variables is fulfilled.

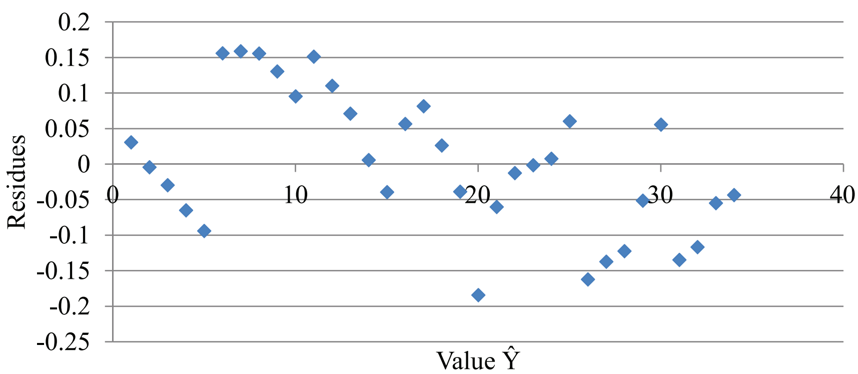

Fig. 3. Dependence of residues on the predicted values

By making sure through residue analysis that the linear multiple regression model is adequate, it is possible to determine whether there is a statistically significant interrelation between the dependent variable and the set of explanatory variables. Since the model includes several explanatory variables, the null and alternative hypotheses are formulated as follows: H_0: $\beta_1=\beta_2=...=\beta_k=0$, H_1: there is at least one value of $\beta_j \neq 0$ (there is a linear interrelation between the recall and at least one explanatory variable).

To test the null hypothesis that there is no linear dependence, the F-criterion is applied: at the level of significance α the null hypothesis H_0 is rejected if $F>F_{U\,(k,\,n-k-1)}$, otherwise the hypothesis H_0 is not rejected. The result of testing the null hypothesis is given in Table 6.

Table 6

Summary table of variance analysis to test the hypothesis of statistical significance of regression coefficients

	df	*SS*	*MS*	*F*	Significance *F*
Regression	3	1.417036	0.472345	45.37929	2.89E-11
Residues	30	0.312265	0.010409	–	–
Total	33	1.729301	–	–	–

If the significance level is 0.05, the critical value of the F-distribution with 3 and 30 degrees of freedom is $F_{U\,(2,31)}$= =0.11606.

According to Table 6, the F-statistic is $45.3793>F_{U\,(2,31)}$= =0.11606 and the p-value is close to $0.000<0.05$. Thus, the null hypothesis H_0 is rejected, and the increase in electric power at the generator terminals is linearly linked with at least one of the explaining variables (inlet water temperature, steam load factor, contamination thickness).

The results of the t-test application are obtained by the Analysis Package for each of the independent variables included in the regression model. Thus, the effect of inlet water temperature:

$$t_1 = 11.0603,$$

effect of steam load:

$$t_2 = 6.05163,$$

effect of contamination thickness:

$$t_3 = 1.87229.$$

If the significance level is 0.05, the critical values of the t-distribution with 30 degrees of freedom are $t_L=-2.3595$ and $t_U=2.3595$. p-value=0. Based on one of the inequalities $t=6.05163>2.3595$ or $p=0.0000<0.05$, the null hypothesis H_0 is rejected. Therefore, at a fixed temperature and contamination thickness, there is a statistically significant dependence between variable X_2 (steam load factor) and power gain. Thus, there is an extremely small probability of discarding the null hypothesis if there is no linear dependence between the steam load factor and the power gain.

Similarly, it has been determined that with a fixed steam load factor and contamination thickness, there is a statistically significant dependence between variable X_1 (inlet temperature) and power gain.

For the third factor $t=1.87229<2.3595$, however, p-value=$0.035<0.05$. Therefore, at a fixed temperature and a steam load factor between a variable X_3 (contamination thickness) and an increase in power, a linear dependence is not observed, but this does not mean that there is no dependence at all, because the last one may be non-linear.

Instead of testing the general population slope hypothesis, we can estimate the value of this slope. To build a confidence interval the multiple regression model uses the formula:

$$b_j \pm t_{n-k-1} \cdot S_{bj}; \qquad (14)$$

where t is a test statistic having a t-distribution with $n-k-1$ degrees of freedom; b_j is the slope of the variable x_j with respect to the variable Y if all other explanatory variables are constants; S_{bj} is the standard error of the regression coefficient b_j.

According to formula (14), a 95 % confidence interval is built, containing the slope of the general population β_1 (the effect of temperature X_1 on the increase in power Y when fixing the contamination thickness X_3 and the steam load factor X_2). Since $b_1=-0.03906$, $S_{b1}=0.00353$, the critical value of t-statistics at the 95 % confidence level and 30 degrees of freedom $t_{n-k-1}=2.3595$, obtained:

$-0.04739 \leq \beta_1 \leq -0.03073.$

Thus, taking into account the effect of contamination and steam load, it can be argued that when the inlet water temperature increases by one degree, the increase reduses by an amount that ranges from 30 to 47 kW. There is a 95 % chance that this interval correctly estimates the dependence between two variables. Since this confidence interval does not contain zero, it can be argued that the regression coefficient β_1 has a statistically significant effect on power gain.

Similarly, the influence of the steam load X_2 on the power gain Y when fixing the contamination thickness X_3 and the temperature X_1) is considered. Since b_2=–1.91899, S_{b2}=0.3171, obtained:

$1.17078 \leq \beta_2 \leq 2.66719.$

Therefore, considering the effect of contamination and temperature, it can be argued that with an increase in steam load, the increase in power grows by an amount that ranges from 1.17 to 2.66 MW. There is a 95 % chance that this interval correctly estimates the dependence between two variables.

6. Discussion of results of studying change in the turbine plant electric power under various states of the condenser

Considering the obtained dependence (13) due to the condenser modernization, the average value of electric power increase at the terminals of the generator of the nuclear power plant power unit is 3.20628 MW. According to Table 6, it was found that with an increase in the inlet water temperature by one degree, the increase reduces by an amount that ranges from 30 to 47 kW. At the same time, with an increase in steam load, the increase grows by an amount that ranges from 1.17 to 2.66 MW.

The proposed approach showed that the presence of air leakages leads to a softening of vacuum in the condensers and should be taken into account in the automatic diagnostics systems of turbine equipment to clarify hourly forecasts of electricity generation. Reducing the increase in electricity generation due to the effects of the analysed factors can partially or even completely absorb the effect of modernization of the condenser plant (Table 2).

This study was carried out on the range of inputs indicated in Table 2, so the expansion of the number of statistical data will help to clarify the parameters of equation (13) and the limits of change of influencing factors, with a corresponding increase in adequacy.

The dependence between the thickness of the condenser heat exchange surface contamination and the power increase at the terminals of the generator of the nuclear power plant power unit is not finally established. This requires the introduction of additional empirical correlations, in particular those used in [16], which will make the simulation model more detailed and accurate.

The study of the dependence between the heat exchange surface contamination thickness of the condenser and the power increase at the terminals of the generator of the nuclear power plant power unit may be the purpose of a separate study. It is possible to use thermodynamic modeling with obtaining of dynamic reviews of condenser for stepwise change of various control parameters [17].

7. Conclusions

1. It was assumed that the planned (reference) increase in electric power at the generator terminals after the reconstruction of the condenser according to the “block-modular” principle will be 0.9–5.2 MW. Despite various structural measures to seal the tube attachment assembly in the tube boards, leakages of cooling water into the steam space of the condenser still appears. Also, during operation, contamination on the heat exchange surface of the condenser is inevitable. To evaluate the analysis of the excellence of the heat transfer process, the feasibility of comparing the reference and real operating modes of the plant by the energy generation volume indicator was confirmed.

2. Empirical dependence of electric power of turbine plant on appearance of air leakages, inlet water temperature and contamination of heat exchange surface is established. Obtained analytical dependence of change of electric power on generator terminals made it possible to determine limits of its change. In particular, taking into account the effect of contamination and steam load, when the inlet water temperature increases by one degree, the increase grows by a value in the range from 30 to 47 kW. Taking into account contamination and temperature changes, with an increase in steam load, the increase grows by an amount that ranges from 1.17 to 2.66 MW.

3. The presence of air leakages leads to a softening of vacuum in the condensers and should be taken into account in the automatic diagnostics systems of turbine equipment to clarify hourly forecasts of electricity generation. Reducing the increase in electricity generation as a result of the effects of the study factors (up to 2.66 MW) can partially or even completely absorb the effect of upgrading the condenser plant (0.9–5.2 MW). Obtaining information on the technical condition of the condenser and its effect on the amount of electric power generation will allow taking the necessary measures in a timely manner to prevent the discharge of power units to search for water leakages. This underlines the importance of the results of diagnostics and monitoring of the technical condition of condenser devices of steam-turbine plants in order to more accurately predict the generation of electric energy for sale to the energy market.

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