5. Gandel' Y. V., Polyanskaya T. S. *Matematicheskie voprosy metoda diskretnykh zaryadov. Ucheb. posobie. Ch. I* [Mathematical problems of the method of discrete charges. Tutorial. Part I]. Kharkov, Kharkov State University Publ., 1991. 67 p.
6. Gandel' Y. V., Eremenko S. V., Polyanskaya T. S. *Матеmaticheskie voprosy меtoda diskretnykh tokov. Ucheb. posobie. Ch. II* [Mathematical problems of the method of discrete currents. Textbook. Part II]. Kharkov, Kharkov State University Publ., 1992. 145 p.
7. Ivanov V. V. *Teoriya priblizhennykh metodov i yeye primeneniya k chislennomu resheniyu singulyarnykh integral'nykh uravneniy* [Approximate methods theory and its application to numerical solving of singular integral equations]. Kiyev, Naukova dumka Publ., 1968. 288p.
8. Korneychuk A. A. Kvadraturnyye formuly dlya singulyarnykh integralov [Quadrature formulae for singular integrals]. In: *Chislennyye metody resheniya differentsial'nykh i integral'nykh uravneniy i kvadraturnyye formuly* [Numerical methods for solving differential and integral equations and quadrature formulae]. Moscow, Nauka, 1964. pp. 64–74.
9. Natanson I. P. *Konstruktivnaya teoriya funktsiy* [Constractive theory of functions]. Moscow –Leningrad, GTTI Publ., 1949. 688 p.
10. Gandel' Y. V. *Lektsii o chislennykh metodakh dlya singulyarnykh integral'nykh uravneniy. Ucheb. posobie. Ch. I* [Lectures on numerical methods for singular integral equations. Textbook. Part I]. Kharkov, V. N. Karazin Kharkov National University Publ., 2001. 92 p.
11. Gabdulkhaev B. G. *Optimal'nye approksimatsii resheniy lineynykh zadach* [Optimal approximation of solutions to linear problems]. Kazan, Izd. Kazanskogo. Universiteta Publ., 1980. 231 p.

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MODELING NPP POWER UNIT STEAM TURBINE INSTALLATION STEAM SEPARATOR-SUPERHEATER TEMPERATURE CHARACTERISTICS BY INTERVAL ANALYSIS METHODS

The determination of the temperature characteristics of one of the significant elements of the wet-steam turbines of nuclear power units – the steam separator-superheater is considered: namely the construction of the dependence of the temperature of the heated steam at the outlet of the second stage on the changing load of the power unit. Modeling is carried out taking into account the error limitation without reliable information about its distribution. To evaluate the coefficients of empirical dependence, constructed according to the results of experimental data, it is proposed to use numerical methods of interval analysis. The interval approach allows building a refined tube, guaranteed to contain acceptable dependences of the temperature of the heated steam on the electric power of the power unit. In a situation of data uncertainty and limited errors, numerical methods of interval analysis allow creating models of processes and equipment of NPP units with the maximum possible correspondence to a real object.

Key words: equipment of NPP power units, steam separator-superheater, temperature characteristics, uncertainty, processing of experimental data, non statistical measurement errors, interval analysis, interval model.

Т. В. ПОТАНІНА, О. В. ЄФІМОВ, Г. Л. ХАВІН

МОДЕЛЮВАННЯ ТЕМПЕРАТУРНИХ ХАРАКТЕРИСТИК СЕПАРАТОРА-ПАРОПЕРЕГРІВНИКА ПАРОТУРБІННОЇ УСТАНОВКИ ЕНЕРГОБЛОКА АЕС МЕТОДАМИ ІНТЕРВАЛЬНОГО АНАЛІЗУ

Розглянуто визначення температурних характеристик одного із значущих елементів вологопарових турбін енергоблоків АЕС – сепаратора-пароперегрівника: побудова залежності від навантаження енергоблоку температури пари, що нагрівається, на виході з другого ступеня. Моделювання здійснюється з врахуванням обмеженості похибки вимірювань без вірогідної інформації про її розподіл. Для оцінювання коефіцієнтів емпіричної залежності, що конструюється за результатами експериментальних даних, пропонується застосування чисельних методів інтервального аналізу. Інтервальний підхід дозволяє побудувати уточнену трубку, яка гарантовано містить припустимі залежності температури пари, що нагрівається від електричної потужності енергоблоку. В ситуації невизначеності даних та обмеженості похибок чисельні методи інтервального аналізу дозволяють створювати моделі процесів та устаткування енергоблоків атомних електростанцій з максимально можливою їх відповідністю реальному об’єкту.

Ключові слова: обладнання енергоблоків АЕС, сепаратор-пароперегрівник, температурні характеристики, невизначеність, обробка експериментальних даних, нестатистичні похибки вимірювань, інтервальний аналіз, інтервальна модель.

Т. В. ПОТАНИНА, А. В. ЕФИМОВ, Г. Л. ХАВИН

МОДЕЛИРОВАНИЕ ТЕМПЕРАТУРНЫХ ХАРАКТЕРИСТИК СЕПАРАТОРА-ПАРОПЕРЕГРЕВАТЕЛЯ ПАРОТУРБИННОЙ УСТАНОВКИ ЭНЕРГОБЛОКА АЭС МЕТОДАМИ ИНТЕРВАЛЬНОГО АНАЛИЗА

Рассмотрено определение температурных характеристик одного из значимых элементов влажнопаровых турбин энергоблоков АЭС – сепаратора-пароперегревателя: построение зависимости температуры нагреваемого пара на выходе из второй ступени от изменяющейся нагрузки энергоблока. Моделирование выполняется с учетом ограниченности погрешности измерений без достоверной информации о ее распределении. Для оценивания коэффициентов эмпирической зависимости, конструируемой по результатам экспериментальных данных, предлагается применение численных методов интервального анализа. Интервальный подход позволяет построить уточненную трубку, гарантировано содержащую допустимые зависимости температуры нагреваемого пара от электрической мощности энергоблока. В ситуации неопределенности данных и ограниченности ошибок численные методы интервального анализа позволяют создавать модели процессов и оборудования энергоблоков атомных электростанций с максимально возможным их соответствием реальному объекту.

Ключевые слова: оборудование энергоблоков АЭС, сепаратор-пароперегреватель, температурные характеристики, неопределенность, обработка экспериментальных данных, нестатистические погрешности измерений, интервальный анализ, интервальная модель.

Introduction. Solving the problems of increasing the efficiency, reliability and safety of electricity and heat production by nuclear power plants, implementation of the strategy of long-term operation of NPP units whose design lifetime has expired or expires in the near future is a topical and strategic state level problem directly related to the energy sector of Ukraine, energy saving and prevention of large-scale man-made disasters [1].

In this regard, there is a growing demand for the development of new methods for analyzing the quality and safety of the operation of thermal power systems, such as nuclear power plant units, diagnostics and forecasting of equipment reliability. This leads to the search for new and improvement of existing methods of technological process modeling in order to determine the reliability and optimize their parameters, to study the relationship between these parameters when upgrading thermal power facilities control systems. Of particular importance is the use of these methods in systems of intellectual support in the absence, significant limitation or uncertainty of information about changes in the parameters of technological processes during the operation of thermal power systems.

Initial data and problem setting. One of the main tasks arising during the operation of wet-steam turbines is to reduce the moisture content in the flow part of the turbine. An increase in steam humidity can lead to a significant decrease in the internal efficiency of the turbine and erosion of the turbine blades.

Moisture is removed using separation devices.

SPP-1000 steam separator-superheater is used for KhTZ K-500-60/1500 and K-1000-60/1500 turbines of nuclear power units with a WWER-1000 reactor.

The turbine unit is equipped with four steam separators-superheaters. The steam separator-superheater is a vertical cylindrical apparatus consisting of a louver-type separator and a two-stage superheater (surface heat exchanger), which are located in the same housing (Fig. 1).

Wet steam from the turbine high-pressure cylinder (HPC) enters the inlet annular chamber, from which it is distributed through the inlet separator manifolds. The steam dried in the separator enters the annulus of the first stage of the steam superheater, where it is finally dried and partially overheated. Final overheating of the steam occurs at the second stage of the steam superheater. Then the overheated steam from the separator-superheater is sent to the low pressure cylinder (LPC) of the turbine. Heating steam for the first stage of the steam superheater is the steam from the first selection of the turbine high pressure cylinder, while for the second stage it is sharp steam.

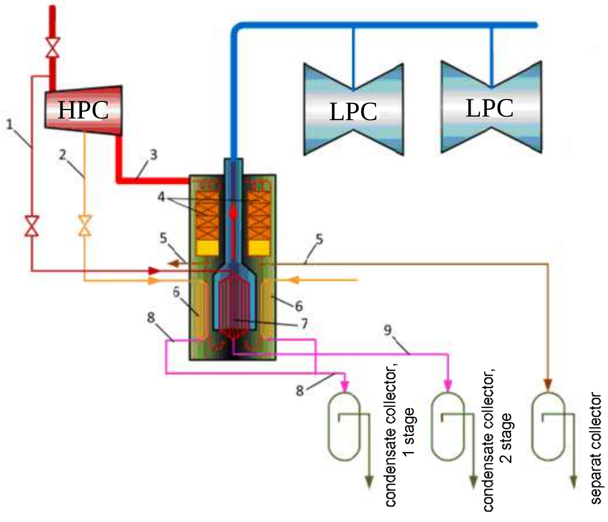

Fig. 1 – Steam separator-superheater installation diagram: 1 – heating fresh steam; 2 – heating steam from the first selection; 3 – wet steam from a high pressure cylinder; 4 – separation bags; 5 – removal of the separat; 6 – superheater of the first stage; 7 – superheater of the second stage; 8 – condensate of heating steam of the first stage; 9 – condensate of heating steam of the second stage.

Consider the problem of determining the temperature characteristics of steam separators-superheaters. Such characteristics, in general, describe the influence of many different factors on the temperature of the heated steam at its outlet with the stages of the steam separator-superheater. One of the important factors is the mode factor, i.e. the change in electrical power (load).

At our disposal are the data of various measurement experiments [2] of the steam temperature at the outlet of the first and second stages when changing the electric power N of the unit in the range $50 \div 100\%$ (Table 1). Temperature values were obtained at the fixed power of the unit.

Table 1 – Thermal test data for the K-1000-60/1500 turbine

N, %	50	60	70	80	90	100
steam temperature at the outlet of the first stage $T1, ^{\circ}C$	180.5	187	192	195	196	198
steam temperature at the outlet of the second stage $T2, ^{\circ}C$	258	257	256	254	252.5	251

It is obvious that the experimental data contain inaccuracies and have interval uncertainty. Uncertainty is caused by measurement and rounding errors, noise, incomplete information. The analysis of numerous scientific works devoted to processing experimental data characterized by uncertainty, shows that an interval model can be considered as one of the most adequate existing models [3 – 16].

It is known that for a wide range of tasks of constructing a mathematical model based on the results of an experiment, the dependence being formalized is the following:

$$y = \varphi(\mathbf{x}, \mathbf{b}) + \varepsilon_y, \qquad (1)$$

where $\mathbf{x} = (x_1, ..., x_n) \in X$ is the vector of input variables; $\mathbf{b}$ – the vector of model parameters; y – the output variable; φ – the function describing the deterministic component of the dependence of y on $\mathbf{x}$, and ε_y – the value describing the uncertainty of the presented dependence.

In the probabilistic model, which is the most common among other methods of constructing a model of the dependence between the input and output variables, the component ε_y is a normally distributed random variable, with a mean of zero and standard deviation σ_y. The uncertainty of the variable y for a given confidence level is described by a confidence interval (the rule «2-σ»):

$$\hat{y} - 2\sigma_y \le y \le \hat{y} + 2\sigma_y, \qquad (2)$$

where $\hat{y}$ is the point estimate of the unknown quantity obtained as a result of the experiment.

The interval model [3] does not impose any requirements on the absolute error ε_y to be given by any distribution law, but only considers its limitations: $|\varepsilon_y| \le \varepsilon$. What, in fact, is accepted in metrology is the assumption that the value $\hat{y}$ is obtained using an inaccurate instrument with a known error ε_y. And then for any value of $\hat{y}$ there is an interval of uncertainty:

$$\mathbf{y} = \left[\hat{y} - \varepsilon_y, \hat{y} + \varepsilon_y\right], \qquad (3)$$

moreover, the interval can always be extended when new sources of errors are detected and their quantitative evaluation is possible.

Many factors influence the uncertainty of temperature measurements using thermocouples and resistance thermometers that measure the temperature of the heart carrier (vapor) at atomic power plants. The basic ones are: random effects when measuring; measurement uncertainty of the recording instrument; tolerance class of thermocouple and resistance thermometer; change in the characteristics of the thermocouple and resistance thermometer over a period of time between checks. There are also several factors specific for a thermocouple such as: the accuracy class of the extension wires connecting the thermocouple to the recording device and the temperature compensation error of the reference junctions. According to the “Guide to the Expression of Uncertainty in Measurement” [17], the uncertainties generated by the listed sources are considered random variables that obey a normal, uniformly symmetric or uniformly asymmetric distribution.

The sample presented in Table 1 contains a rather limited number of experimental points – only six measurements, and the structure and probabilistic characteristics of the measurement errors are unknown. Thus, it is impossible to justify the use of standard procedures for processing the experimental data, which rely on statistical methods such as: representative sample (it should be of sufficient length), normality of the distribution of measurement errors (the error is probabilistic and its distribution is normal and unbiased), accuracy of the values of the main argumen.

In such a situation, applying numerical methods of interval analysis provides more complete information on the dependence of the vapor temperature on the load [18 – 19].

Results and their discussion. We briefly introduce the basic principles of interval arithmetic [3]. Any interval number (range) can be written in the form of some closed real interval $\mathbf{a} := [\underline{\mathbf{a}}, \overline{\mathbf{a}}]$, where $\underline{\mathbf{a}} < \overline{\mathbf{a}}$ [3]. In the case of

$\mathbf{a}=\overline{\mathbf{a}}=\underline{\mathbf{a}}$, the interval $\mathbf{a}$ is identified with a real number a. The width of any interval $\mathbf{a}$ is defined as $w(\mathbf{a})=\overline{\mathbf{a}}-\underline{\mathbf{a}}$. The middle (center) of the interval is $\operatorname{mid}(\mathbf{a})=\dfrac{\overline{\mathbf{a}}+\underline{\mathbf{a}}}{2}$. The interval radius is defined as $\operatorname{rad}(\mathbf{a})=\dfrac{\overline{\mathbf{a}}-\underline{\mathbf{a}}}{2}$. The absolute value (module) of the interval is $|\mathbf{a}|=\max\left\{|\overline{\mathbf{a}}|,|\underline{\mathbf{a}}|\right\}$.The interval $\mathbf{a}$ determines the set of possible values of the unknown true parameter a. In the interval approach, no probabilistic or fuzzy measures in the range (interval) $\mathbf{a}$ are specified, i.e. all values within the interval are considered equally probable (not identical to the uniform distribution of a random variable).

The interval operations are carried out according to the following rules:

1. Addition $\mathbf{a}+\mathbf{b}=\left[\underline{\mathbf{a}}+\underline{\mathbf{b}},\ \overline{\mathbf{a}}+\overline{\mathbf{b}}\right]$.
2. Subtraction $\mathbf{a}-\mathbf{b}=\left[\underline{\mathbf{a}}-\overline{\mathbf{b}},\ \overline{\mathbf{a}}-\underline{\mathbf{b}}\right]$.
3. Multiplication $\mathbf{a}\times\mathbf{b}=\left[\min\left(\underline{\mathbf{a}}\cdot\underline{\mathbf{b}},\ \underline{\mathbf{a}}\cdot\overline{\mathbf{b}},\ \overline{\mathbf{a}}\cdot\underline{\mathbf{b}},\ \overline{\mathbf{a}}\cdot\overline{\mathbf{b}}\right),\ \max\left(\underline{\mathbf{a}}\cdot\underline{\mathbf{b}},\ \underline{\mathbf{a}}\cdot\overline{\mathbf{b}},\ \overline{\mathbf{a}}\cdot\underline{\mathbf{b}},\ \overline{\mathbf{a}}\cdot\overline{\mathbf{b}}\right)\right]$.
4. Division $\dfrac{\mathbf{a}}{\mathbf{b}}=\left[\underline{\mathbf{a}},\ \overline{\mathbf{a}}\right]\times\left[\dfrac{1}{\overline{\mathbf{b}}},\ \dfrac{1}{\underline{\mathbf{b}}}\right]$, and besides $0\notin\mathbf{b}$.
5. Multiplication by scalar $k\cdot\mathbf{a}=\begin{cases}\left[k\underline{\mathbf{a}},\ k\overline{\mathbf{a}}\right], & k\geq 0\\ \left[k\overline{\mathbf{a}},\ k\underline{\mathbf{a}}\right], & k<0\end{cases}$.

In the interval model, the inaccuracy or uncertainty of the output parameter (which in our task is the steam temperature t) is described by the interval $\mathbf{t}=[\underline{\mathbf{t}},\overline{\mathbf{t}}]$, where $\underline{\mathbf{t}}$ and $\overline{\mathbf{t}}$ are the lower and upper bounds of this interval respectively. The interval defines the set of possible values of the unknown true parameter t. The peculiarity of the interval approach is that no probabilistic or fuzzy measure is set within the interval $\mathbf{t}$, that is, all values within the interval are equally possible.

Assume that the output steam temperature at the outlet of the second stage of steam separator-superheater t depends linearly on the electrical load of the unit N (%):

$$t(N,b1,b2)=b1+b2\cdot N+\varepsilon\,, \tag{4}$$

where $b1, b2$ are parameters.

The following values from (4) are to be estimated: the membership set $I(b1,b2)$ of the actual values of the parameters and the range of the actual values of the dependence (4).

The experimental data are presented by the sample:

$$\left\{T2_i, N_i,\ i=1,\ldots,n\right\}, \tag{5}$$

where $T2_i$ is the observation of the dependence; N_i are the values of the argument; $n=6$ is the sample length (Fig. 2).

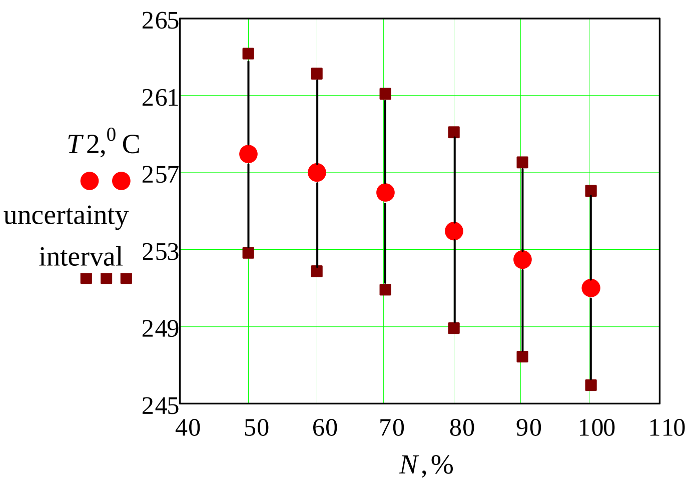

Fig. 2 – Experimental data: $T2$, $^{\circ}C$ – steam temperature at the outlet of the second stage recorded at the specified level of electrical load N, % of the unit [2]; vertical posts – uncertainty intervals.

We assume that the values N_i are known exactly. Although the values of electric power in the conditions of thermal tests of a turbine unit are also determined with some error. For the most accurate measurement of the electric power at the terminals of the generator, the following measures are taken:

- choosing measuring transformers with the actual error in the operating range of measurements up to $\pm(0.1 \div 0.2)\%$ and adopting of measures that reduce errors to a minimum (due to the difficulty of accounting for the latter). In particular, in order to avoid overload, it is necessary to check the actual load of the measuring transformers, minimizing it;
- eliminating harmful effects on the accuracy of measurement;
- connecting measuring instruments as close as possible to the output terminals and to any branch through which leakage or supplementary supply of energy can occur;
- using two independent measurement methods simultaneously.

The measurement of temperature values $T2$ are assumed to contain noise errors. Resistance thermocouples that measure the temperature of the heat carrier (vapor) at atomic power plants have the device error $\pm(0.15+0.002|t|)\,^{\circ}C$ or $\pm(0.3+0.005|t|)\,^{\circ}C$, depending on the tolerance class [20]. In addition, the given error should be taken into account, the value of which is indicated in the metrological standards. The reduced measurement error takes into account all the components of the parameter measurement: methodological, instrumental, and subjective. When measuring the temperature of the steam in the pipeline behind the steam separator-superheater, the reduced error for direct control is 1.5 %, the readings and registration by the secondary devices are determined with an error of 2 %.

That is, for each experimental value:

$$T2_i = \widehat{T2}_i + \varepsilon_i,\ |\varepsilon_i| \le \varepsilon_{\max},\ \ i = 1, ..., 6, \tag{6}$$

where $T2_i$ is the result of the vapor temperature measurement; $\widehat{T2}_i$ denotes the unknown true value of the temperature; ε_i is the i-measurement error; the maximum value of the error $\varepsilon_{\max}$ is about $5^{\circ}\mathrm{C}$.

For each vapor temperature measurement the lower $\underline{\mathbf{T}2_i}$ and upper $\overline{\mathbf{T}2_i}$ bounds of the uncertainty interval $\mathbf{T}2_i$ are calculated using model (3):

$$\mathbf{T}2_i = \left[\underline{\mathbf{T2_i}}, \overline{\mathbf{T2_i}}\right],\ i = 1, ..., 6,\ \underline{\mathbf{T2_i}} = T2_i - \varepsilon_{\max},\ \overline{\mathbf{T2_i}} = T2_i + \varepsilon_{\max}. \tag{7}$$

In the physical sence the uncertainty interval is the range of possible values of the vapor temperature that contains the unknown true value.

The set of the uncertainty intervals shown in Fig. 2:

$$\{\mathbf{T}2_i\} = \{[252.84, 263.16], [251.86, 262.14], [250.88, 261.12], [248.92, 259.08], [247.45, 257.55], [245.98, 256.02]\}. \tag{8}$$

Each uncertainty interval $\mathbf{T}2_i$, $i = 1, ..., 6$ contains possible values of the measured value, consistent with this measurement, that is, at least one curve of dependence (4) can be drawn through *all* intervals of uncertainty.

For each pair of the intervals $\mathbf{T}2_i$ and $\mathbf{T}2_j$, $i = 1, ..., 5,\ j = i+1, ..., 6$, of uncertainties of the sample measurements given by (7) – (8), a two-dimensional *partial membership set* $G_{i,j}(b1, b2)$ of parameters $b1, b2$ [18] compatible with the given pair of uncertainty intervals is calculated.

The next step is to determine the membership set $I(b1, b2)$ of the parameters $b1, b2$ compatible with the entire sample of measurements:

$$I(b1, b2) = \bigcap\nolimits_{i=1,...,5,\ j=i+1,...,6} G_{i,j}(b1, b2). \tag{9}$$

From (4) and (7) follow the constraints for the membership set:

$$T2_i - \varepsilon_{\max} \le b1 + b2 \cdot N_i \le T2_i + \varepsilon_{\max},\ i = 1, ..., 6. \tag{10}$$

Accordingly, these conditions take the form:

$$\begin{gathered} 252.84 \le b_1 + 50 \cdot b_2 \le 263.16, \\ 251.86 \le b_1 + 60 \cdot b_2 \le 262.14, \\ 250.88 \le b_1 + 70 \cdot b_2 \le 261.12, \\ 248.92 \le b_1 + 80 \cdot b_2 \le 259.08, \\ 247.45 \le b_1 + 90 \cdot b_2 \le 257.55, \\ 245.98 \le b_1 + 100 \cdot b_2 \le 256.02. \end{gathered} \tag{11}$$

The formal application of the rule for constructing a membership set leads to the following result: the set $I(b1, b2)$

is a polygon with seven vertices, and the parameter $b2$ takes values of different signs:

$$\{(b1,\, b2)\} = \{(252.84,\, 0),\, (249.66,\, 0.0636),\, (256.02,\, 0),\, (257.74,\, -0.098),\, (262.31,\, -0.16333),$$
$$(280.34,\, -0.3436),\, (270.3,\, -0.1428)\}. \qquad (12)$$

However, the analysis of experimental data (Table 1) and the principles of the process of drying and superheating of steam in a separator-superheater show that dependence (4) is a function that decreases with increasing electric power. Therefore, it makes sense to require that parameter $b2 < 0$. Accordingly, with the new restriction on the parameters, the membership set $I(b1, b2)$ takes the form of a polygon with six vertices (Fig. 3 – the gray region):

$$I(b1, b2):\ \mathbf{b}^1 = (b1,\, b2) = (252.84,\, 0),\ \ \mathbf{b}^2 = (256.02,\, 0),\ \ \mathbf{b}^3 = (270.3,\, -0.1428),\ \ \mathbf{b}^4 = (280.34,\, -0.3436),$$
$$\mathbf{b}^5 = (262.31,\, -0.16333),\ \ \mathbf{b}^6 = (257.74,\, -0.098). \qquad (13)$$

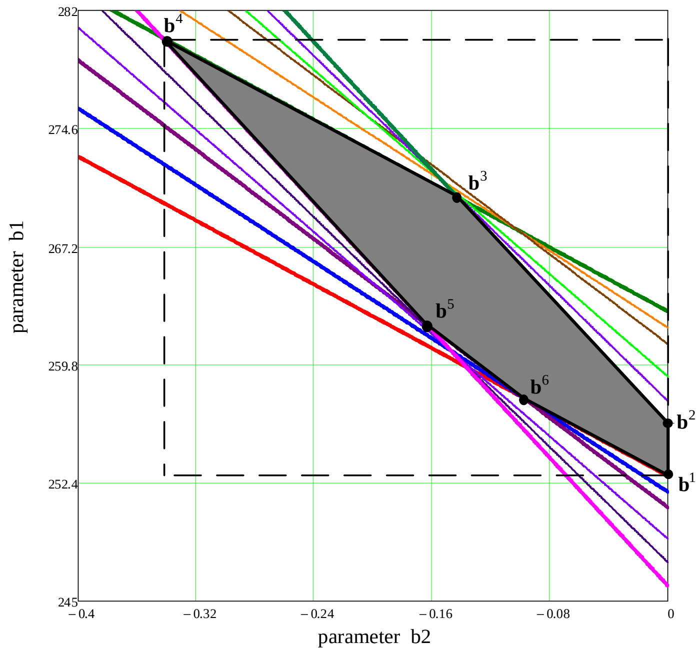

Fig. 3 – The membership set $I(b1, b2)$.

This set is characterized by the unconditional minimal external estimates which are the parameter intervals $\left[\underline{\mathbf{b1}}, \overline{\mathbf{b1}}\right]$ and $\left[\underline{\mathbf{b2}}; \overline{\mathbf{b2}}\right]$. These intervals are determined according to the rules:

$$\mathbf{b1} = \left[\underline{\mathbf{b1}}; \overline{\mathbf{b1}}\right] : \underline{\mathbf{b1}} = \mathrm{Arg}\{\min b1 \in I(b1,\, b2)\},\ \ \overline{\mathbf{b1}} = \mathrm{Arg}\{\max b1 \in I(b1,\, b2)\}; \qquad (14)$$

$$\mathbf{b2} = \left[\underline{\mathbf{b2}}; \overline{\mathbf{b2}}\right] : \underline{\mathbf{b2}} = \mathrm{Arg}\{\min b2 \in I(b1,\, b2)\},\ \ \overline{\mathbf{b2}} = \mathrm{Arg}\{\max b2 \in I(b1,\, b2)\}. \qquad (15)$$

The extreme corner points defining the size of the set $I(b1, b2)$ (rectangle marked with dotted lines in Fig. 3) and the boundaries of the intervals $\mathbf{b1}$ and $\mathbf{b2}$ are $\mathbf{b}^1 = (252.84,\, 0)$, $\mathbf{b}^4 = (280.34,\, -0.3436)$. Thus,

$$\mathbf{b1} = [252.84,\, 280.34],\ \ \mathbf{b}2 = [-0.3436,\, 0]. \qquad (16)$$

The interval approach allows to construct a refined tube $t(N)$ of guaranteed – valid dependencies. Such a tube is defined by its lower $\underline{t}(N_i)$ and upper $\bar{t}(N_i)$ limits, which are calculated using the membership set in the following way:

$$\mathbf{t}(N) = \{\underline{t}(N_i),\, \bar{t}(N_i)\},\ \ i = 1, \ldots, 6, \qquad (17)$$

where $$\underline{t}(N_i) = \min_{(b1,b2)\in I(b1,b2)} \{b1 + b2 \cdot N_i\},\ \ \bar{t}(N_i) = \max_{(b1,b2)\in I(b1,b2)} \{b1 + b2 \cdot N_i\}.$$

Namely (Fig. 4)

$$\{\underline{t}(N_i)\} = \{252.84,\, 251.86,\, 250{,}877,\, 249.224,\, 247.61,\, 245.977\},$$
$$\{\bar{t}(N_i)\} = \{263.16,\, 261.732,\, 260.304,\, 258.876,\, 257.448,\, 256.02\}.$$

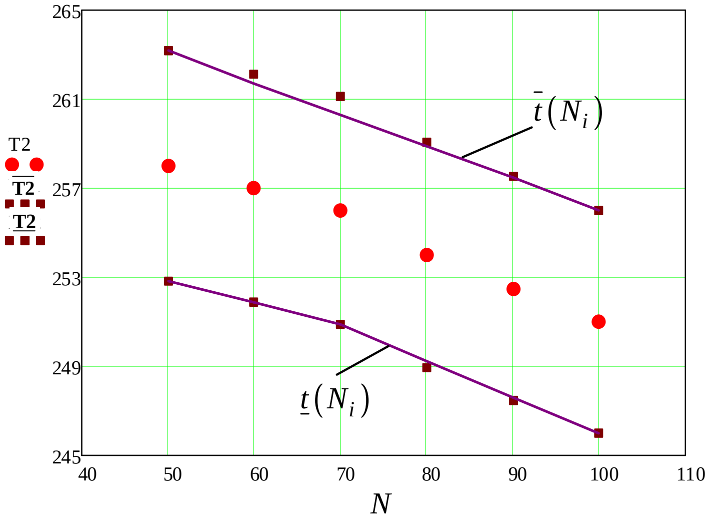

Fig. 4 – The boundaries of the tube of actual values.

It should be noted that at some points the actual value tube is narrower than the uncertainty intervals.

The interval model of the dependence of steam temperature at the outlet of the second stage on electric power can be represented as:

$$[t(N)] = [252.84, 280.34] + [-0.3436, 0] \cdot N \, . \tag{18}$$

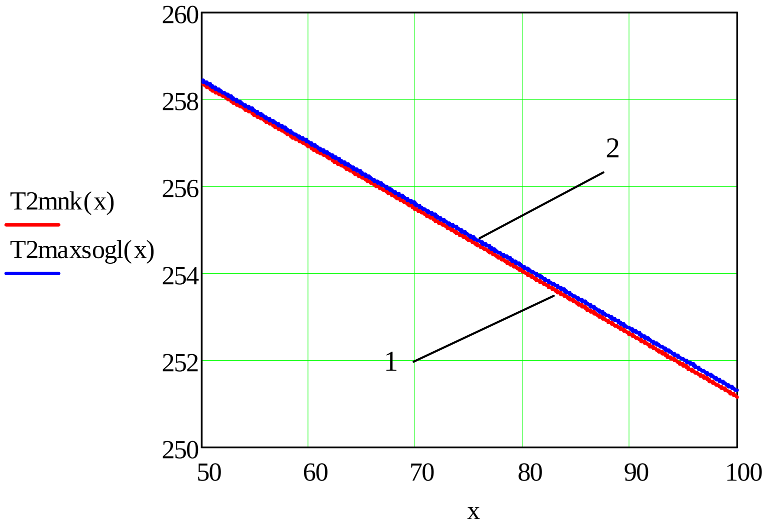

Fig. 5 – Forecast models for the dependence of steam temperature on electric power:
line 1 – LSM-estimation, line 2 – estimate constructed using the maximum compatibility method.

Using the point estimates of the parameters $\hat{b}1, \hat{b}2$ of the unknown coefficients of the output variable model (steam temperature at the outlet of the second stage) with a fixed vector of the input variable (electric power), it is possible to construct a point estimate defining some prediction model. The parameter estimates obtained by applying the *uncertainty center method* [21] are:

$$\hat{b}1_c = 0.5\left(\underline{\mathbf{b1}} + \overline{\mathbf{b1}}\right), \; \hat{b}2_c = 0.5\left(\underline{\mathbf{b}2} + \overline{\mathbf{b}2}\right), \tag{19}$$

$$\hat{b}1_c = 266.59, \; \hat{b}2_c = 0.1718 \, .$$

Accordingly, the direct forecast is the following:

$$\hat{t}(N) = 266.59 - 0.1718 \cdot N \, . \tag{20}$$

Using standard statistical approaches for processing experimental data, we determine the parameters of relation (4) by *the least squares method* [21]. The resulting equation is:

$$\hat{t}(N) = 265.571 - 0.144 \cdot N \, , \tag{21}$$

the mean square deviation is $\sigma = 0.333$. Least squares linear approximation graph is shown in Fig. 5 (line1).

Another assessment was performed using *the maximum compatibility method*. This method was proposed by *Shary S. P.* [12, 19] to restore dependencies from data with interval uncertainty and as a solution determines the points at which the best agreement of the data with the dependence parameters is achieved. The desired dependency has the form:

$$\hat{t}(N) = 265.588 - 0.1428 \cdot N \ . \quad (22)$$

In the problem under consideration, the point estimates (21) and (22) of the parameters are fairly close.

Conclusion. When solving problems of safety and reliability assessment of systems and equipment of NPP units, as well as improving their efficiency by determining operational (energy) characteristics, the problem of taking into account uncertainty factors in the objects and processes for which models are created, as well as choosing mathematical tools for their description remains relevant. The classic "point-by-point" representation of values in modeling and optimization problems often does not allow to reach the maximum possible correspondence between a real object and its model. Ignoring the interval nature of the problem leads to a solution in the form of certain "exact" numbers, and the closeness of such solutions to the lower possible and, accordingly, the upper possible values of the interval cannot be estimated. In the practice of operating NPP units this can result, in a number of cases, in erroneous decisions when solving problems of process optimization, as well as assessing safety and reliability indicators.

In this situation, the advantages of data processing, model defining and constructing by means of interval analysis methods are quite obvious, as their means allow to take into account inaccuracies in setting the initial data, measurement errors, uncertainties of parameters and system model, multimode nature of the operation of such complex systems as NPP units. Therefore, the use of the mathematical tools of interval analysis, its capabilities and advantages is promising for solving a wide range of problems connected with safety and reliability assessment, increase in the efficiency of NPP units based on correct operational characteristics in condition of the uncertainty of initial data.

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Bibliography

1. Доповідь про стан ядерної та радіаційної безпеки в Україні в 2018 році. – Київ, 2019. – 70 с. – Режим доступу : http://www.snrc.gov.ua/nuclear/doccatalog/document?id=425406. – Дата звертання : 01 січня 2020.
2. *Бузлуков В. А., Теплицкий М. Г., Ойберман Л. Б., Ефимов А. В., Палагин А. А., Меньшикова Е. Д.* Получение характеристик оборудования турбоустановок методом натурно-вычислительного эксперимента // Теплоэнергетика. – 1987. – № 8. – С.19 – 21.
3. *Moore R. E., Kearfott R. B., Cloud M. J.* Introduction to interval analysis. – Philadelphia : Society for Industrial and Applied Mathematics, 2009. – 223 p.
4. *Потанина Т. В., Ефимов А. В., Гаркуша Т. А., Есипенко Т. А.* Применение методов интервального анализа для оценки безопасности и надежности энергоблоков АЭС // Ядерна та радіаційна безпека. – 2018. – № 3 (79). – С. 23 – 29.
5. *Jaulin L., Kieffer M., Didrit O., Walter E.* Applied Interval Analysis. – London : Springer – Verlag Limited Publ., 2001. – 379 p.
6. *Дивак М. П.* Задачі математичного моделювання статичних систем з інтервальними даними. – Тернопіль : Економічна думка ТНЕУ, 2011. – 216 с.
7. *Gutowski M. W.* Interval experimental data fitting // Focus on Numerical Analysis. – NY : Nova Science Publishers, 2006. – P. 27 – 70.
8. *Вощинин А. П.* Интервальный анализ данных: развитие и перспективы // Заводская лаборатория. Диагностика материалов. – 2002. – Т. 68. – № 1. – С. 118 – 126.
9. *Крюков А. В., Литвинцев А. И.* Интервальное моделирование режимов электроэнергетических систем в фазных координатах // Современные технологии. Системный анализ. Моделирование. – 2014. – № 4(44). – С. 57 – 62.
10. *Родионова О. Е.* Интервальный метод обработки результатов многоканальных экспериментов : дис. … д-ра физ.-мат. наук : 01.04.01. – Москва, 2008. – 273 с.
11. *Grishkevich A.* Interwałowe oszacowania wskaźników niezawodności strukturalnej systemów elektroenergetycznych na podstawie metod optymalizacji // Prace naukowe Akademii im. Jana Długosza w Częstochowie. "Technika, Informatyka, Inżyneria Bezpieczeństwa". – 2014. – vol. II. – pp. 91 – 106.
12. *Shary S. P.* Maximum consistency method for data fitting under interval uncertainty // Journal of Global Optimization. – 2016. – vol. 66. – issue 1. – pp. 111 – 126.
13. *Kreinovich V., Shary S. P.* Interval methods for data fitting under interval uncertainty: a probabilistic treatment // Reliable Computing. – 2016. – vol. 23. – pp. 105 – 140.
14. *Yefimov A. V., Pylypenko M. M., Potanina T. V., Yesypenko T. A., Harkusha T. A., Stadnik Yu. S.* Processing of experimental data of the process of refining nuclear material Zr1%Nb by electron-beam melting by means of interval analysis methods // ВАНТ. – 2019. – № 5 (123). – С. 118 – 123.
15. *Потаніна Т. В., Єфімов О. В.* Застосування методів інтервального аналізу для визначення експлуатаційних характеристик енергоблоків АЕС // Bulletin of the National Technical University «KhPI». Series : Hydraulic machines and hydraulic units. – 2019. – № 2. – С. 77 – 81.
16. *Yefimov A. V., Potanina T. V.* Application of interval analysis for improving reliability of estimation of hardness value spread for nuclear structural materials // ВАНТ. – 2020. – № 1 (125). – С. 206 – 210.
17. Guide to the Expression of Uncertainty in Measurement : First edition. – ISO, Switzerland, 1993. – 101 c.
18. *Кумков С. И.* Обработка экспериментальных данных ионной проводимости расплавленного электролита методами интервального анализа // Расплавы. – 2010. – № 3. – С. 79 – 89.
19. *Шарый С. П.* Задача восстановления зависимостей по данным с интервальной неопределенностью // Заводская лаборатория. Диагностика материалов. – 2020. – Т. 86. – № 1. – С. 62 – 74.

20. ДСТУ 2858:2015. Термоперетворювачі опору. Загальні технічні вимоги і методи випробувань // Нац. стандарт України. – Київ : Мінекономрозвитку України, 2017. – 22 с.

21. *Жилин С. И.* Эксперименты по оцениванию параметров эмпирической зависимости методом наименьших квадратов и методом центра неопределенности // Известия Алтайского государственного университета. – 2003. – № 1. – С. 24 – 27.

22. *Линник Ю. В.* Метод наименьших квадратов и основы теории обработки наблюдений. – Л. : Физматгиз, 1962. – 352 с.

References (transliterated)

1. *Dopovid' pro stan yadernoyi ta radiatsiynoyi bezpeku v Ukrayini v 2018 rotsi* [Report on the State of Nuclear and Radiation Safety in Ukraine in 2018]. Available at : http://www.snrc.gov.ua/nuclear/ doccatalog/document?id=425406 (accessed 01.01.2020).

2. Buzlukov V. A., Teplitskiy M. G., Oyberman L. B., Efimov A. V., Palagin A. A., Men'shikova Ye. D. Poluchenie kharakteristik oborudovaniya turboustanovok metodom naturno-vychislitel'nogo eksperimenta [Obtaining the characteristics of the turbine units equipment by the full-scale computing experiment method]. *Teploenergetika* [Heat power engineering]. 1987, no. 8, pp. 19–21.

3. Moore R. E., Kearfott R. B., Cloud M. J. *Introduction to interval analysis.* Society for Industrial and Applied Mathematics. Philadelphia, 2009. 223 p.

4. Potanina T. V., Yefimov A. V., Garkusha T. A., Yesipenko T. A. Primeneniye metodov interval'nogo analiza dlya otsenki bezopasnosti i nadezhnosti energoblokov AES [Application of interval analysis methods for NPP power units safety and reliability assessment]. *Yaderna ta radiatsiyna bezpeka* [Nuclear and radiation safety]. 2018, no. 3 (79), pp. 23–29.

5. Jaulin L., Kieffer M., Didrit O., Walter E. *Applied Interval Analysis.* London, Springer–Verlag Limited Publ., 2001. 379 p.

6. Dyvak M. P. *Zadachi matematychnogo modeluvannya statychnykh system z interval'nymy danymy* [Problems of mathematical simulation of static systems with interval data]. Ternopil', Ekonomichna dumka Publ., 2011. 216 p.

7. Gutowski M. W. Interval experimental data fitting. *Focus of Numerical Analysis.* New York, Nova Science Publishers, 2006. pp. 27–70.

8. Voshhinin A. P. Interval'nyy analiz dannykh : razvitiye i perspektivy [Interval data analysis: development and prospects]. *Zavodskaya laboratoriya. Diagnostika materialov* [Industrial laboratory. Materials diagnostics]. 2002, vol. 68, no. 1, pp. 118–126.

9. Kryukov A. V., Litvintsev A. I. Interval'noye modelirovaniye rezhimov elektroenergeticheskikh system v faznykh koordinatakh [Interval simulation of electrical power systems modes in phase coordinates]. *Sovremennyye tekhnologii. Sistemnyy analiz. Modelirovaniye* [Modern technologies. System analysis. Simulation]. 2014, no. 4(44), pp. 57–62.

10. Rodionova O. Ye. *Interva'lnyy metod obrabotki rezul'tatov mnogokanal'nykh eksperimentov : dis. … d-ra fiz.-mat. nauk 01.04.01* [Interval method for processing the results of multichannel experiments. Dr. phis.– mat. sci. diss.]. Moscow, 2008. 273 p.

11. Grishkevich A. Interwalowe oszacowania wskaznikow niezawodnosci strukturalnej systemow elektroenergetycznych na podstawie metod optymalizacji. *Prace naukowe Akademii im. Jana Dlugosza w Czestochowie. "Technika, Informatyka, Inzyneria Bezpieczenstwa".* 2014, vol. II, pp. 91–106.

12. Shary S. P. Maximum consistency method for data fitting under interval uncertainty. *Journal of Global Optimization.* 2016, vol. 66, issue 1, pp. 111–126.

13. Kreinovich V., Shary S. P. Interval methods for data fitting under interval uncertainty: a probabilistic treatment. *Reliable Computing.* 2016, vol. 23, pp. 105–140.

14. Yefimov A. V., Pylypenko M. M., Potanina T. V., Yesypenko T. A., Garkusha T. A., Stadnik Yu. S. Processing of experimental data of the process of refining nuclear material Zr1%Nb by electron-beam melting by means of interval analysis methods. *PAST.* 2019, no. (123), pp. 118–123.

15. Potanina T. V., Yefimov O. V. Zastosuvannya metodiv interval′noho analizu dlya vyznachennya ekspluatatsiynykh kharakterystyk enerhoblokiv AES [Application of interval analysis method for determining operating characteristics of NPP power units]. *Bulletin of the National Technical University "KhPI". Series : Hydraulic machines and hydraulic units.* 2019, no. 2, pp. 77–81.

16. Potanina T. V., Yefimov A. V. Application of interval analysis for improving reliability of estimation of hardness value spread for nuclear structural materials. *PAST.* 2020, no. 1 (125), pp. 206–210.

17. *Guide to the Expression of Uncertainty in Measurement : First edition.* ISO, Switzerland, 1993. 101 p.

18. Kumkov S. I. Obrabotka eksperimental'nykh dannykh ionnoy provodimosti rasplavlennogo elektrolita metodami interval'nogo analiza [Processing of experimental data on the ionic conductivity of molten electrolyte by interval analysis methods]. *Rasplavy* [Melts]. 2010, no. 3, pp. 79–89.

19. Shary S. P. Zadacha vosstanovleniya zavisimostey po dannym s interval'noy neopredelennost'yu [Data fitting problem under interval uncertainty in data]. *Zavodskaya laboratoriya. Diagnostika materialov* [Industrial laboratory. Materials diagnostics]. 2020, vol. 86, no. 1, pp. 62–74.

20. *DSTU 2858:2015. Termoperetvoryuvachi oporu. Zagal'ni tekhnichni vymogy i metody vyprobuvan'* [State Standard 2858:2015. Thermo-converters of resistance. General technical requirements and test methods]. Kyiv, Ministry of Economic Development and Trade of Ukraine Publ., 2017. 22 p.

21. Zhilin S. I. Eksperimenty po otsenivaniyu parametrov empiricheskoy zavisimosti metodom naimen'shikh kvadratov i metodom tsentra neopredelennosti [Experiments on the estimation of empirical dependence parameters by the least squares method and the method of center of uncertainty]. *Izvestiya Altayskogo gosudarstvennogo universiteta* [News of the Altai State University]. 2003, no. 1, pp. 24–27.

22. Linnik Yu. V. *Metod naimen'shykh kvadratov i osnovy teorii obrabotki nablyudeniy* [Least squares method and the basics of observation processing theory]. Leningrad, Fizmatgiz Publ., 1962. 352 p.

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