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AUTOMATION AND HEAT CONTROL IN POWER ENGINEERING

Algorithms for Striking Material and Energy Balances in Calculating the Technical-and-Economic Indicators of Thermal Power Plant Equipment Based on the Ill-Posed Problem Regularization Method

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Abstract—The problem of striking material and energy balances from the data received by thermal power plant computerized automation systems from the technical accounting systems with the accuracy determined by the metrological characteristics of serviceable calibrated instruments is formulated using the mathematical apparatus of ridge regression method. A graph theory based matrix model of material and energy flows in systems having an intricate structure is proposed, using which it is possible to formalize the solution of a particular practical problem at the stage of constructing the system model. The problem of striking material and energy balances is formulated taking into account different degrees of trustworthiness with which the initial flow rates of coolants and their thermophysical parameters were determined, as well as process constraints expressed in terms of balance correlations on mass and energy for individual system nodes or for any combination thereof. Analytic and numerical solutions of the problem are proposed in different versions of its statement differing from each other in the adopted assumptions and considered constraints. It is shown how the procedure for striking material and energy balances from the results of measuring the flows of feed water and steam in the thermal process circuit of a combined heat and power plant affects the calculation accuracy of specific fuel rates for supplying heat and electricity. It has been revealed that the nominal values of indicators and the fuel saving or overexpenditure values associated with these indicators are the most dependent parameters. In calculating these quantities using different balance striking procedures, an error may arise the value of which is commensurable with the power plant thermal efficiency margin stipulated by the regulatory-technical documents on using fuel. The study results were used for substantiating the choice of stating the problem of striking material and fuel balances, as well as the method for solving it. With the problem statement and the solution method implemented in the real thermal power plant computerized automation systems, less biased calculation of actual thermal efficiency indicators of equipment is obtained.

Keywords: thermal power plant thermal efficiency, technical accounting system, material balance, energy balance, ill-posed problem, regularization method

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Striking material and energy (thermal and electrical) balances is one of the stages of work on determining the actual values of technical-economic indicators (TEIs) characterizing the performance of equipment used at thermal power plants [1].

Balance discrepancy may be caused not only by the metrological imperfectness of accounting instruments, but also by their inoperability or even temporary unavailability. In the majority of cases, the system of balance equations written for some process circuit is not fully defined, due to which it yields the most plausible but not exact solution. The accuracy of the solution depends essentially on the initial imbalance. This is why the guiding document [2] specifies the limiting discrepancy of the material balance of thermal power plants (TPPs) from the indications of accounting instruments at a level of 2–3%.

The most essential drawbacks of the guiding documents [1, 2] in the field of assuring the measurement quality of main parameters involved in TEI calculations are as follows:

(i) They prescribe checking the convergence of material balance only with respect to one most significant process loop (in particular, from the boiler feed water flow meters to the turbine unit live steam flow meters) without taking into account the balances in the other parts of the TPP process circuit.

(ii) The prescribed maximum admissible imbalance has an a fortiori overestimated value, which does not take into account different degrees of trustworthiness of determining the initial values of each parameter in particular cases.

(iii) Material balances are struck without matching them with energy balances, which does not allow one

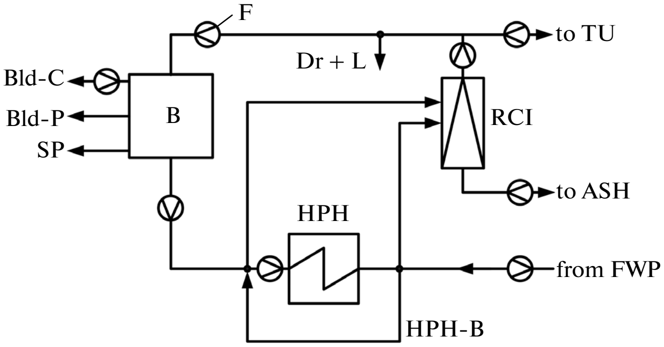

Fig. 1. Fragment of the power system structural diagram. FWP are the feedwater pumps, HPH is the group of high-pressure heaters, HPH-B is the HPH group bypass by water (the "cold" riser), B is the boiler, Bld-C and Bld-P are the boiler continuous and periodic blowdown circuits, SP are sampling points, Dr + L are drains and leaks, RCI are live steam reducing and cooling installations (including the startup and fast-acting ones), TU is the turbine unit, ASH is the auxiliary steam header, and F is a flow meter.

to estimate the quality of coolant flow pressure and temperature measurements.

In practice, the above-mentioned drawbacks lead to essential errors in TEI calculations. For example, for the conditions existing at the OMSK TETs-4 combined heat and power plant (CHP), the increase of material balance discrepancy in the main steam line circuit by 1% results in the error of determining the overexpenditure of fuel in the average winter mode of operation equal to around 500 tce per month. The material balance discrepancy equal to 1% in the auxiliary steam pipework system operating at a pressure of 0.8–1.3 MPa is equivalent to the error in determining the overexpenditure of fuel more than 280 tce per month (it should be noted that the typical material balance discrepancies by the measured indicators for auxiliary steam pipelines are as a rule an order of magnitude higher than the above-mentioned value equal to 1%). With the existing approach to estimating the validity of technical accounting system data, the above-mentioned expenditures can be attributed to imperfectness of operation or to poor technical state of equipment, and the reported TPP thermal efficiency indicators will become distorted.

Thus, development of calculation algorithms that make it possible to strike balances with taking into account different degrees of trustworthiness in determining the parameters of initial information, as well as metrological and process-related constraints for all or certain selected nodes of the thermal process circuit is a problem topical from the viewpoint of achieving less biased calculation of TPP equipment's technical and economic indicators. This work is devoted to development of such algorithms. Given a totality of parameter measurement results and a complex of obvious balance relations these data should comply with, the following question is to be answered: whether the calculated discrepancies of balances on the monitored process circuit nodes are due to the nominal errors of the monitoring system, or the increased discrepancies on all or some nodes are due to inoperability of instruments or due to the fact that their indications go beyond the limits of their nominal metrological characteristics. In the latter case, it is important to locate the error source.

For solving the problem being considered, it is advisable to use the Tikhonov regularization method commonly known as the ridge regression method [3]. In the given case, the regularization concept boils down to searching for a reasonable tradeoff between the minimal discrepancy value of balances for all nodes and the minimal mismatch between the solution and initial information. In accordance with the ridge regression method's terminology, we will call this initial information, which includes the indications of accounting instruments and expert estimates for non-measured parameters, a priori information.

By applying the ridge regression concept [3], the initial ill-posed problem

$$\mathbf{AY} + \sigma = \mathbf{B} \tag{1}$$

is brought to the problem of minimizing the following function:

$$F_c(\mathbf{Y}, \lambda) = |\mathbf{AY} - \mathbf{B}|^2 + \lambda |\mathbf{Y} - \mathbf{Y}_0|^2 \Rightarrow \min, \tag{2}$$

where $\mathbf{Y}$ and $\mathbf{Y}_0$ are the sought regularized solution and its a priori estimate, $\mathbf{A}$ and $\mathbf{B}$ are the known operators of the system model, σ is the numerical parameter characterizing the error of the equation right-hand side, and λ is the small positive regularization parameter, which should be selected in a certain manner. In minimizing the function $F_c(\mathbf{Y})$, the regularized solution $\mathbf{Y}(\lambda)$ depending on the parameter λ is obtained.

For using the regularization method in analyzing the validity of coolant flows measurement results, it is necessary to construct the mathematical model of the studied plant, i.e., to determine the form of operators **A** and **B**. The procedure of constructing the model of material flows is illustrated below taking as an example a section of the thermal process circuit of a power unit equipped with a drum-type steam boiler. The structural diagram of this circuit with indicating the coolant flow rate measurement points is shown in Fig. 1.

For describing the system structure we introduce the directed graph $G = (\mathbf{X}, \mathbf{V})$ [4]. The flow mixing and distribution points will be regarded as the graph nodes (X), and the pipelines between these points will be represented by the corresponding branches of the graph (V_j). Some parallel pipelines can be represented in the graph by one branch without sacrificing the generality of the approach. The structure of the graph $G = (\mathbf{X}, \mathbf{V})$ for the considered example is shown in Fig. 2. For the possibility of checking and striking the balance for the entire system, the external flows in the circuit are conditionally let into the first node. The external links at nodes *1*, *2*, and *4* shown by dashed arrows will be needed later during simultaneous consideration of material and energy balances in the system.

For describing the system structure in the model, we use the graph incidence matrix, the construction procedure of which is illustrated by Table 1. Each line of the table is related to the corresponding node of graph X_i, and each of its columns is related to the graph branch V_j. If the beginning of the graph *j*th branch lies in the *i*th node, the corresponding entry in the incidence martix is equal to unity ($a_{ij} = 1$). If the end of the graph *j*th branch lies in the *i*th node, the corresponding entry in the incidence matrix is equal to minus unity ($a_{ij} = -1$).

The incidence matrix **A** of dimension $n \times m$ ($n = 7$ is the number of graph lines or nodes, and $m = 12$ is the number of graph columns or branches) constructed in the above-mentioned manner has the following form for the example considered:

$$\mathbf{A} = \begin{pmatrix} 1 & 0 & 0 & -1 & 0 & 0 & -1 & -1 & -1 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & -1 & -1 \end{pmatrix}.$$

The product of the incidence matrix **A** by the vector **V** yields the matrix **AV**, each entry of which corresponds to the mass imbalance at the relevant node. With this approach, the known statement of ill-posed problem (1) can be written, taking into account the above-mentioned comments and the introduced notation ($\mathbf{B} = 0$, $\mathbf{Y} = \mathbf{V}$), in the following form:

$$\mathbf{AV} + \sigma = 0, \tag{3}$$

where the incidence matrix is used as the operator **A**.

For solving the problem taking into account different degrees of trustworthiness in determining individual a priori information parameters (different metrological characteristics of measurement tools or their serviceability and accuracy of expert estimates), we proposed the vector regularization method. In this case, the number of regularization parameters coincides with the number of a priori information parameters, and the diagonal matrix of regularization parameters λ must be used instead of the scalar quantity **λ**.

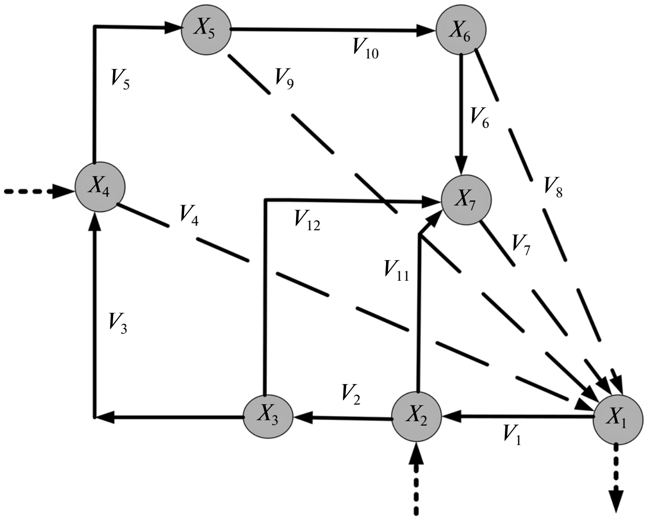

Fig. 2. Structure of the graph $G = (\mathbf{X}, \mathbf{V})$ corresponding to the process circuit shown in Fig. 1. X_1 is the uniting of system external flows; X_2 and X_3 denote feed water upstream and downstream of the HPH, respectively; X_4 is the boiler; X_5 is the conditional location point of drains and leaks from the main steam lines; X_6 is steam extraction to the RCI, and X_7 is the RCI. Flow rates: V_1—feed water from the FWP; V_2—feed water through the HPH and HPH-B (total); V_3—feed water to the boiler; V_4—medium from Bld-C, Bld-P, and SPs (total); V_5—steam from the boiler; V_6 and V_7—steam on the RCI hot and cold sides; V_8—steam to the turbine; V_9—with drains and leaks from the main steam lines; V_{10}—steam from the boiler minus the drains and leaks from the main steam lines; and V_{11} and V_{12}—cold and hot feed water for injection into the RCI.

In view of the above-mentioned comments, the formulation of optimization problem (2) becomes

with the scalar statement:

$$F_c(\mathbf{V}, \lambda) = |\mathbf{AV}|^2 + \lambda |\mathbf{V} - \mathbf{V}_0|^2 \Rightarrow \min; \tag{4}$$

Table 1. Construction of the graph incidence matrix for the process circuit shown in Fig. 1

X	V											
	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}
X_1	1	0	0	1	0	0	1	−1	−1	0	0	0
X_2	1	1	0	0	0	0	0	0	0	0	1	0
X_3	0	−1	1	0	0	0	0	0	0	0	0	1
X_4	0	0	−1	1	1	0	0	0	0	0	0	0
X_5	0	0	0	0	−1	0	0	0	1	1	0	0
X_6	0	0	0	0	0	1	0	1	0	−1	0	0
X_7	0	0	0	0	0	−1	1	0	0	0	−1	−1

with the vector statement:

$$F_c(\mathbf{V},\lambda) = |\mathbf{AV}|^2 + |\lambda(\mathbf{V} - \mathbf{V}_0|)\,|^2 \Rightarrow \min. \quad (5)$$

The first term in objective function (4) or (5) shows the total discrepancy of balances for all nodes $\Delta = |\mathbf{AV}|$, and the second term characterizes the modulus of the vector representing the deviation of the obtained solution from the initial vector $\Delta\mathbf{V} = |\mathbf{V} - \mathbf{V}_0|$.

In solving the problem, the metrological and process-related constraints must also be taken into account

$$V_i \in [V_i^{\min}; V_i^{\max}]; \quad (6)$$

$$\Delta G_i \in [0; \Delta G_i^{\max}], \quad (7)$$

where $V_i^{\min}$ and $V_i^{\max}$ are the boundaries of the confidence interval in which the actual value of the parameter exists, which are stemming from the nominal error of the serviceable measurement tool (or expert estimate), and $\Delta G_i^{\max}$ is the maximum admissible imbalance of mass at the nodes due to the measurement tool errors within the nominal metrological characteristics of the monitoring system.

The analytic solution of problem (4) or (5) can be obtained without taking into account constraints (6) and (7):

with the scalar statement (the solution is known [3])

$$\mathbf{V} = (\mathbf{A}^{\mathrm{T}}\mathbf{A} + \lambda\mathbf{E})^{-1}\lambda\mathbf{V}_0; \quad (8)$$

with the vector statement (the solution was obtained by differentiating equations (5) with respect to the sought parameters and equating the derivative to zero)

$$\mathbf{V} = (\mathbf{A}^{\mathrm{T}}\mathbf{A} + \lambda^2\mathbf{E})^{-1}\lambda^2\mathbf{V}_0, \quad (9)$$

where $\mathbf{E}$ is the identity matrix, and the superscripts "T" and "−1" denote matrix transposition and inversion, respectively.

For numerically solving optimization problem (4) or (5) taking constraints (6) and (7) into account, it is proposed to use statistical programming algorithms [5]. The use of these algorithms involves multiple random generation of the flow rate vector **V** around the a priori values of its elements in the range specified by metrological constraints (6). With solutions generated in such manner, the metrological constraints are automatically fulfilled. After that, the generated solution is checked for fulfilling process-related constraints (7) at the specified nodes. With all constraints fulfilled, the obtained solution versions are compared by the objective function value, and the optimal version is selected from them, which corresponds to the minimal value of objective function (4) or (5). If attempts to find a solution satisfying the specified constraints were not met with success, it should be recognized that some of instruments are faulty, or that they went beyond the boundaries of their nominal metrological characteristics. The problem of locating the error source that arises in this case is solved by searching for the nodes characterized by the maximal imbalances of mass and the branches corresponding to these nodes.

An analysis of the considered solutions was carried out for the power system shown in Fig. 1. The initial data for calculation in the form of flow rate vector in the graph branches $\mathbf{V}_0$ and the solutions of the problem in its different statements are given in Table 2. It should be noted that the calculation example is based on the technical accounting data for a month for the possibility of carrying out subsequent calculation of fuel overexpenditure or saving for the CHP.

The following features of the considered problem solution versions were revealed:

(i) The problem in scalar statement (4) and its analytic solution (8) allow one to find the sought vector of flow rate values in the circuit, but they do not take into account metrological and process-related constraints.

(ii) The problem in scalar statement (4) and its numerical solution allow one to take into account metrological and process-related constraints, but they do not take into account different degrees of trustworthiness of determining the results from measuring individual parameters, i.e., the differences in the metrological characteristics of measurement tools operating as part of the monitoring system.

(iii) The problem in vector statement (6) and its numerical solution allow one to obtain a solution with taking into account metrological and process-related constraints, as well as different degrees of trustworthiness of determining the results from measuring individual parameters. It is exactly this version that is recommended for being practically implemented in the TPP computerized automation system.

Analytic solutions (8) and (9) do not take into account constraints (6) and (7), due to which they are of no interest for practical applications; however, they are useful for checking the correctness of the results from solving the considered problem according to the numerical method.

The obtained results allow one to solve the stated problem of checking whether the data obtained from the coolant flow rates monitoring system are consistent with the nominal metrological characteristics of the used measurement tools, which is in compliance with the requirements of regulatory documents [1, 2]. However, the considered statement of the problem does not allow the material and energy balances in the system to be matched with each other.

In accordance with the requirements of regulatory documents [1, 2], energy balances are struck directly in determining the actual TEIs of equipment operation. In so doing, the coolant flow rate values are taken from the results of striking material balances (this striking is carried out without taking into account the constraints imposed by energy balances); the flow pressure and temperature values are taken from the data of actual measurements, and the convergence of energy balances is achieved by adjusting the coolant

Table 2. Initial (a priori) information used for the calculation and the results of solving the regularization problem

Indicator	Graph branch number i											
	1	2	3	4	5	6	7	8	9	10	11	12
Initial flow rate value $V_{0j} \times 10^{-6}$, t/month*	1.0157*	1.0596*	1.0571*	0.0127	1.0394*	0.0294*	0.0357*	0.9938*	0.0022	1.0232	0.0015	0.0025
Error of determining the initial flow rate values, %	2.3	1.1	0.9	5.2	1.2	1.8	2.2	1.1	8.5	2.1	1.2	1.5
Enthalpy, h_i, kJ/kg	691.9*	954.5*	960.1*	1594.9*	3488.2*	3487.5*	2991.2*	3478.4*	3488.2*	3488.2*	691.9*	954.5*
Error of determining the initial enthalpy values, %	1.76	1.65	1.76	1.85	1.50	1.53	1.32	1.46	1.50	1.50	1.76	1.65
Solution of the material flows regularization problem (without taking energy flow constraints into account) $V_i \times 10^{-6}$, t/month												
Analytic solution for scalar statement of the problem (4)	1.0240	1.0560	1.0542	0.0110	1.0381	0.0296	0.0335	0.9917	0.0017	0.0248	–0.0046	0.0114
Numerical solution for scalar statement of the problem (4)	1.0443	1.0440	1.0438	0.0189	1.0249	0.0296	0.0301	0.9946	0.0007	1.0242	0.0003	0.0002
Numerical solution for vector statement of the problem (5) with taking constraints (6) and (7) into account	1.0267	1.0544	1.0534	0.0127	1.0338	0.0296	0.0359	0.9900	0.0023	1.0235	0.0015	0.0025
Solution of the simultaneous material and energy flows regularization problem												
Using:												
the additive criterion:												
$V_i \times 10^{-6}$, t/month	1.0375	1.0514	1.0505	0.0133	1.0282	0.0293	0.0351	0.9871	0.0021	1.0225	0.0015	0.0025
$H \times 10^{-6}$, GJ/month	0.7074	1.0001	1.0026	0.0213	3.5366	0.1016	0.1056	3.4542	0.0072	3.5204	0.0011	0.0024
the multiplicative criterion												
$V_i \times 10^{-6}$, t/month	1.0365	1.0558	1.0528	0.0129	1.0271	0.0291	0.0356	1.0026	0.0022	1.0354	0.0015	0.0024
$H \times 10^{-6}$, GJ/month	0.7251	1.0029	1.0055	0.0209	3.6294	0.1026	0.1066	3.5229	0.0077	3.6333	0.0010	0.0023

1. The symbol "*" denotes measured parameters. 2. For the problem statement versions with taking process-related constraints into account, the maximal discrepancy of material balance for node 1 equal to 2% is adopted as a process-related constraint, which is consistent with [2].

flow power values themselves. With such an approach, the thermal (power) loads of equipment are not matched with coolant flow rates and their thermophysical characteristics. Therefore, in order to achieve more reliable results of determining the actual TEIs of equipment operation, it is advisable to impose requirements on the primary data processing algorithms according to which they should check the convergence of not only material, but also energy balances in the system. In view of this circumstance, it is advisable that the solution of considered problem (4) or (5) be found taking into account the balance relations for the power of coolant flow rates.

In constructing energy balances we will separate two kinds of energy flows: an inner and an outer one. The energy flows connected with the coolant flows inside the system are regarded to be inner ones. The energy flows transferred to coolants into the system from outside (e.g., in the boiler or in the high-pressure heater for the circuit shown in Fig. 1) are regarded to be external for it. In the framework of the ridge regression concept, the initial ill-posed problem is formulated as follows:

$$\mathbf{AV} + \sigma = 0, \quad \mathbf{AH} + \sigma_1 = \mathbf{B}, \tag{10}$$

where $\mathbf{H} = \mathbf{V} \times \mathbf{h}$ is the energy flow vector, $\mathbf{h}$ is the enthalpy vector (the dot before the multiplication symbol denotes term-wise multiplication of the corresponding entries of two vectors), σ and σ_1 are the numerical parameters characterizing the error of the right-hand sides of the equations, and $\mathbf{B}$ is the column matrix that takes into account energy flows that are external for the system.

In solving the simultaneous mass and energy flows regularization problem, it is necessary to minimize two objective functions or two criteria F_{c1} and F_{c2}, i.e., to consider, in fact, a multicriterion optimization problem of the following type (in scalar statement):

$$\left.\begin{aligned} F_{c1}(\mathbf{V},\lambda_1) &= |\mathbf{AV}|^2 + \lambda_1 |\mathbf{V}-\mathbf{V}_0|^2 \Rightarrow \min; \\ F_{c2}(\mathbf{H},\lambda_2) &= |\mathbf{AH}-\mathbf{B}|^2 + \lambda_2 |\mathbf{H}-\mathbf{H}_0|^2 \Rightarrow \min, \end{aligned}\right\} \tag{11}$$

where $\mathbf{H}$ and $\mathbf{H}_0$ is the sought regularized solution and its a priori estimate by energy flows.

Several methods for solving multicriterion problems are known [5, 6], each of which has its advantages and drawbacks. Below, some of these methods are considered.

(1) Replacement of a few optimization criteria by one integral criterion (an additive or a multiplicative one), which is obtained, respectively, by adding or multiplying the initial criteria with the appropriate coefficients of their significance. Relative simplicity of calculations is the advantage of such a solution. On the other hand, such an approach can yield solutions with which, given the minimal sum or product of the criteria, the values of one criterion will compensate the values of another criterion (one criterion "absorbs" another one). In addition, the selection of criterion significance coefficients is in many respects intuitive, i.e., subjective.

(2) Another method for solving multicriterion problems consists in finding a Pareto-optimal or Pareto-efficient solution [7, 8]. Pareto optimality or Pareto set is a set of alternative versions that do not have advantages over the other versions right in all criteria. For our problem, selection of Pareto-optimal alternatives will mean a reasonable compromise between obeying the energy and mass balances in the selected power system.

Below, the multicriterion optimization problem is solved as applied to the example considered above.

For solving this problem, it is necessary to modify the system matrix model by taking into account the external energy flows. The resulting structure of graph $G = (\mathbf{X}, \mathbf{V})$ for the process circuit considered in the example is shown in Fig. 2. The external energy flows enter into the nodes X_4 (the steam boiler) and X_2 (the group of turbine unit high-pressure heaters), and energy removal is organized from the node X_1 with live steam supplied to the turbine set.

As far as the striking of energy balances is concerned, the previously considered problem is suplemented with the following relation for energy: $\Delta\mathbf{E} = \mathbf{AH}$. Expressions for the optimization criteria by mass and energy that take metrological and process-related constraints into account can be written in the following form (in vector statement):

$$F_{c1}(\mathbf{V},\boldsymbol{\lambda}_1) = |\mathbf{AV}|^2 + |\boldsymbol{\lambda}_1(\mathbf{V}-\mathbf{V}_0)|^2 \Rightarrow \min; \tag{12}$$

$$V_i \in [V_i^{\min}; V_i^{\max}]; \tag{13}$$

$$\Delta G_i \in [0; \Delta G_i^{\max}]; \tag{14}$$

$$F_{c2}(\mathbf{H},\boldsymbol{\lambda}_2) = |\mathbf{AH}|^2 + |\boldsymbol{\lambda}_2(\mathbf{H}-\mathbf{H}_0)|^2 \Rightarrow \min; \tag{15}$$

$$h_i \in [h_i^{\min}; h_i^{\max}]; \tag{16}$$

$$\Delta E_i \in [0; \Delta E_i^{\max}], \tag{17}$$

where $\boldsymbol{\lambda}_1$ and $\boldsymbol{\lambda}_2$ are the diagonal matrices of small positive parameters of regularization by mass and energy, respectively; $h_i^{\min}$ and $h_i^{\max}$ are the boundaries of confidence intervals corresponding to existence of actual enthalpy values that are stemming from the nominal errors of measurement tools; and $\Delta E_i^{\max}$ are the maximum admissible energy imbalances at the nodes caused by the measurement tool errors within the limits of the monitoring system's nominal metrological characteristics.

The initial data in the form of a priori flow rate values in the graph branches V_i and enthalpies of these flows h_i are given in Table 2, which also indicates the nominal error limit values of determining the corresponding parameters.

The problem will be solved using the statistical programming method, the description of which was given previously. The results of solution carried out with

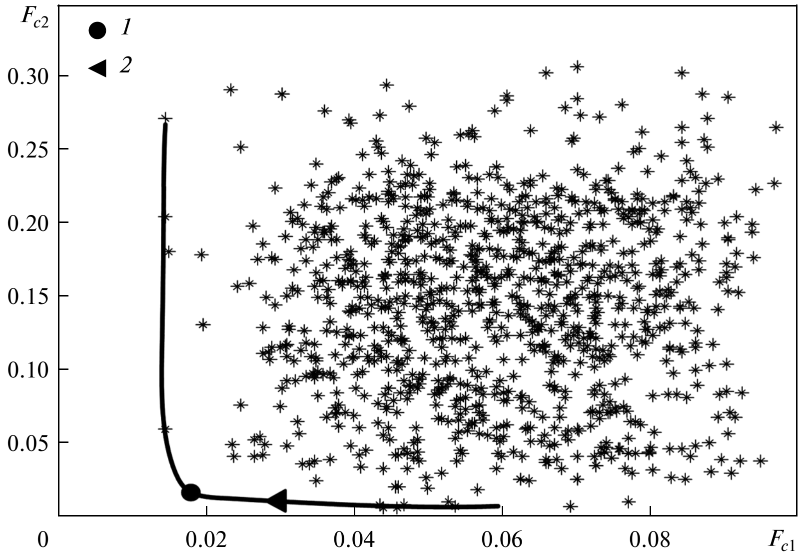

Fig. 3. Results from numerical solution of the multicriterion optimization problem. F_{c1} and F_{c2} are the values of optimization criteria according to (12) and (15), * is the set of analyzed versions, and solid curve is the Pareto set. (*1*) and (*2*) are the solutions obtained using the additive and multiplicative criterion, respectively.

replacing two optimization criteria by the additive and multiplicative criteria are given in Table 2. In both cases, the solutions were obtained with the equal criterion significance values. For solving the multicriterion problem using the Pareto set, we denote all alternatives satisfying the specified metrological constraints by points in the (F_{c1}, F_{c2}) coordinate system. The calculation results are shown in Fig. 3. It can be seen that by applying the additive and multiplicative criterion we obtain solutions that are part of the Pareto set.

Using the Pareto set in solving the problem is convenient if it is necessary to find answers to the following questions: whether the imbalances of mass and energy observed in the system are due to the nominal metrological characteristics of measurement tools, and whether it is necessary to find regularized values of coolant flow rates and energy in the thermal circuit. In this case, it is sufficient to impose constraints on the obtained set of solutions corresponding to the technologically permissible values of total mass and energy imbalances. If the vertical and horizontal lines corresponding to these constraints intersect each other above and/or to the right of the curve describing the Pareto set, a positive answer should be given to the stated questions; otherwise, the regularization problem does not have a solution. The necessary error source location is carried out by selecting the node with the maximal imbalance of mass and/or energy.

The use of the proposed generalization of the material and energy flows regularization problem makes it possible to ensure a more trustworthy subsequent calculation of the actual TEIs of equipment operation. The numerical approach to solving the formulated multicriterion multiparametric optimization problem makes it possible to take into account different degrees of trustworthiness of determining the measurement results of individual parameters, as well as process-related and metrological constraints for the selected nodes or a certain totality thereof.

In conclusion, we will analyze the effect the procedure of striking material balances for the studied example (see Table 2) has on the final indicators of CHP thermal efficiency. Table 3 summarizes the results from calculation of the actual and nominal specific fuel rates at the CHP for the considered month, as well as the thermal efficiency margin (expressed in terms of the total fuel expenditure or saving). The requirements of the regulatory document [1] for striking the CHP thermal, fuel, and electrical balances are fully complied with in each of the calculations. However, different initial values of the main coolant flows obtained from striking the material balance according to the corresponding method were used every time.

It can be seen from the data of Table 3 that the actual values of specific fuel rates are almost independent on the material balance striking procedure because the total expenditure of fired fuel, and the supply of heat and electricity are the data of commercial accounting; i.e., they are characterized by a high degree of trustworthiness. However, the standardized values of specific fuel rates, which depend on the actual loads of each equipment set and, hence, on the balance striking method, vary to a greater extent. Accordingly, the final value of fuel overexpenditure differs for some versions by almost an order of magnitude. Obviously, the calculation results obtained from striking material balances in solving the problem of simultaneous regularization of material and energy

Table 3. Results from calculation of the final TEIs of CHP equipment operation for different versions of determining the initial values of coolant flow rates in the thermal process circuit

Indicator	Without striking a balance	Solution of the material flow regularization problem (without taking into account energy flow constraints)			Solution of the simultaneous material and energy flows regularization problem	
		analytic for scalar statement of the problem (4)	numerical for scalar statement of the problem (4)	numerical for vector statement of the problem (5) with taking constraints (6) and (7) into account	numerical using the additive criterion	numerical using the multiplicative criterion
Specific consumption of equivalent fuel for supplying:						
electricity, gce/(kW h):						
actual	360.5	360.5	360.5	360.5	360.4	360.5
standardized	355.1	357.8	359.8	358.9	357.3	357.4
heat, kgce/GJ:						
actual	43.80	43.80	43.80	43.80	43.83	43.80
standardized	182.4	182.6	183.4	183.1	183.0	183.0
Overexpenditure of fuel for the period, tce	1054	610	117	324	570	545

flows should be regarded as the most representative ones.

The presented example does not pretend for the generality of conclusions regarding the effect the material balance striking method has on the values of the final TEIs of TPP equipment. On the other hand, it demonstrates that this effect may be quite essential. The error caused by incorrect striking of material balance or by lack of work on striking balances is commensurable with the sought indicator, i.e., the equipment thermal efficiency margin.

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