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MATHEMATICAL MODDELING AND INVESTIGATION OF THE HEAT-SUPPLY CIRCUIT FOR A HEAT POWER MINISTATION WORKING ON HULL

This method of mathematical modeling makes it possible to consider a large number of prospective heat-supply circuits and to modernize the existing heat supply circuits of boiler houses and heat power electric stations. On the basis of the given method a system for computer-aided design of the heat supply circuit has been created.

Key words*: industrial boiler house, heat power plant, oil-extraction enterprise, mathematical modeling, logic-computational simulation, graph, arc, information network, mnemonic circuit.*

Current importance of the problem

The task of increasing the efficiency of gas utilization leads to the transition from standard boiler house heat-supply circuits to the complicated individual schemes that include turbines, internal combustion engines, heat pumps, heat utilizers, etc. The range of fuels, used in boiler houses, is extended by the fuels of vegetative origin, biogases, waste of the processing industry. The system character of the above-mentioned task requires its consideration in combination with environmental, biological, medical, economic and engineering problems.

Design calculations of a boiler house are distinguished by the uncertainty as to some initial data, especially specific cost parameters that undergo changes in the course of future exploitation. The increasing number of circuit elements and of their possible combinations, the extended range of changes in initial data, system character of the problem and the factor of uncertainty complicate considerably the choice of the final variant of a boiler house heat-supply circuit.

Actual importance of the results, obtained in this work, lies in possibility of their application to synthesis and analysis of heat-supply circuits for industrial boiler houses when they are transformed into heat power ministations.

Problem statement

Boiler units and their connections are depicted on heat-supply circuits. Extensive research, design and exploitation of heat-supply circuits for boiler houses are aimed at solving the following problems:

- synthesis of the heat-supply circuits with optimal structures and parameters;

-investigation of the optimized circuit operation in the operating conditions, different from basic ones;

-feasibility study and substantiation of the proposals on the problem of increasing the efficiency of boiler houses, that are in operation.

While solving the problems of the first type, complex optimization of the heat-supply circuit elements is performed that includes the choice of boilers, heat engines, pumps, water treatment system, heat exchangers, tanks, pipe-lines, thermal isolation, etc.

Investigation of the heat-supply circuit in different operation modes is required for strength analysis of the boiler houses equipment components, for the development of protection system, automatic equipment, and alarm system as well as for working out the instructions on the operation of the boiler house units.

The problems of synthesis and analysis of the boiler house heat-supply circuit can be represented mathematically in the following form. The value of the target function must be found with restrictions in the form of equalities and inequalities:

$$F(X, Y, \Lambda, G_j) = 0 \tag{1}$$

$$X^{\min} \le X \le X^{\max}, \qquad Y^{\min} \le Y \le Y^{\max},$$

$$X \in \{X_c, X_d\}, \qquad \Lambda \in \{\Lambda_{dt}, \Lambda_p\},$$

$$G_j \in \Gamma \;,$$

where F is equation system describing processes, design and economic estimates of the equipment of the heat-supply circuit, having structure G_j from the finite set of structures Γ; X_c, X_d – set of continuous and discrete variables correspondingly; Y – set of dependent variables; Λ – set of external determinated parameters Λ_{dt} and probability variables in the time of parameters Λ_p.

Synthesis of the optimal heat-supply circuit is confined to the construction of control according to X, Y, G_j with the purpose of functional optimization. Investigation of the circuit in different operation modes means finding Y values with given values of X, G_j.

Current level of computational research of heat power plants determines the following requirements to the method for solving the problems of boiler plants investigation:

the ability to consider system factors;

the possibility of complex optimization while designing heat-supply circuits and boiler house equipment;

the ability to take into account initial uncertainty.

Boiler house is a component of the heat power supply system of one or more enterprises. Therefore, in the course of detailization there could be the following levels of the heat-supply circuit development:

– choosing configuration of the heat power supply system for the enterprises of a region;
– heat-supply circuit of the boiler house;
– boiler house units.

Analysis of the existing methods

A number of research works deal with the problems of analysis and synthesis of heat-supply circuits for heat power ministations created from industrial boilers houses, e.g. in [1] three-level structure is presented for the synthesis of optimal heat-supply circuit: graph modeling and analysis of the basic heat-supply circuit, synthesis of possible variants, finding the most optimal system.

The author divides the problem into several stages: design elements – apparatus – installation – unit – technological system – boiler house. Informational block-diagram of the boiler house heat-supply circuit is analogous to the graph of the diagram. Each unit is the analog of the graph node and flows are the analog of the graph arc.

Graph is also represented in the form of a material-flow graph, heat-flow graph and exergic graph. Synthesis of the heat-supply circuit is performed with the application of the graph analysis method. The number of input and output flows from each node of the graph is determined. The number and the form of equations represent the mathematical model of the heat-supply circuit.

Technical and economic parameters of the heat-supply circuit are used as its efficiency evaluation criteria. In [2, 3] optimization of the heat-supply circuit is performed as well as its modernization on the basis of technical and economic parameters of several possible variants.

The above-mentioned methods are quite efficient tools for synthesis and analysis of industrial boiler houses, although they do not meet the above requirements and do not take into account the specific problems connected with transformation of a boiler house into a heat power ministation.

Substantiation of the research results

In this paper the problem of synthesis and analysis of the heat-supply circuits is solved with the method that is the development of the mathematicall modeling method for heat-supply circuits of the heat power plants [4]. In this paper this method is applied for modeling of industrial boiler houses and heat power ministations

The following procedures are the main elements of the method:

– representation of the boiler house design and technological structures;

– logic-computational simulation of physical processes occurring in boiler houses;

– adaptation of the mathematical models of the equipment components to the procedures of their calculations in design departments;

– supervision over software realization of the boiler house mathematical model.

The structure of the industrial boiler house is represented in the form of graphs. The elements of equipment are depicted as graph nodes and their connections are presented in the form of graph arcs. Graph arc orientation coincides with the direction of the energy carriers motion. Technological and constructional correspondence of the boiler house equipment to the graph is achieved by assigning codes to its nodes. Encoded (technological) graph has the form of:

$$G^T = (K_n{}^i, N_n{}^i) \Leftrightarrow U_{k=1}^P N_a{}^j, \quad (2)$$

where $K_n{}^i$, N_n^i are constructional-technological codes of node i and arc j ; $U_{k=1}^P$- set of arcs incidental to the node, N_n^i, N_a^i - the number arc j. Indices i and j define the position of N_n^i and N_a^i in the lists of nodes and arc numbers. Graph is interpreted as an information network where flows are energy carrier parameters Yj=(y1,y2,…yn) in technological connections (graph arc), and characteristics Xj=(x1,x2…xm) of the equipment elements (graph nodes) are parameters of the source. The codes of arcs and nodes define the structures of informational groups y1,y2,…yn and x1,x2…xm, and their numbers define the position of these groups in the row of others. On T-graph DF system of logic (decoding) functions is defined. They receive certain object characteristics (codes, terms) of graph elements. With the help of logic functions, statement li(GT,DF) functions (predicates) are built. They adopt the values of 0 or 1 depending on their satisfying certain conditions, e.g. whether the code of the given node from the node codes subjects i belong to the boiler or does not belong to it;

Physical processes in the industrial boiler house are described by the set of conservation equations: of mass, momentum, energy; the equations of entropy gain and the state of the working medium and heat carriers. The main distinguishing feature of this system is the fact that the number and the form of equations of each type depend on the technological installation (the number of apparatus, their purpose, connection means and design), i.e. on logic information. This feature explains why it is expedient to represent mathematical model of an industrial boiler house in the form of a set of logic-numerical operators that reflect the transformation of the forms of equations (numerical functions) depending on the technological codes of the graph nodes and arcs (logic variables) and form automatically the necessary set of equations on the graph. Mathematical model of the boiler house is given by:

$$\Delta З_\Sigma(G^T, I, DF) / \Delta_r LT(G^T, I, DF) = 0, r = 1, 2 \ldots s, \quad (3)$$

where Δ is the symbol of logic-numerical operator; $\Delta З_\Sigma$ – operator of the quality of a boiler house variant;

Lт – identifier of the logic-numerical operator; C_i^{min}, C_i^{max} – graphical values of the parameters of information network I; G^T – technological graph of the boiler house scheme.

Each of the logic-numerical operators is a set of hierarchically subordinated logic-numerical modules with

$$\Delta_r LT\,(G^{T,}\, I, DF) = U^{s}_{r=1}\Delta lt_i\,(G^{T,}\, I, DF), \qquad (4)$$

where lti is logic-numerical module of r level. Module is written as the product of statement and numerical functions:

$$\Delta lt_i(G^{T,} I, DF) = l_i\,(К_в, К_д, DF)*t_i(x,y);\;\; x,y \in I, \qquad (5)$$

where I is statement function; t – numerical function (process equation); x, y – dependent and independent variables.

Mathematical model compatibility with the method of its equipment calculations in design departments is achieved by means of equipment model identification according to experimental (calculated or actual) data.

Model (2) operation includes the following procedures: reviewing graph nodes, finding codes of the nodes and arcs by decoding functions DF and addressing the corresponding codes of the equations transformation nodes. The system is solved by iteration method.

The mathematical model is realized by the system for computer-aided design (CAD system) of boiler house heat-supply circuits. The system comprises mathematical descriptions of industrial boiler, back-pressure and condensing turbines, turbo drive of the feed pump, feed and circulation pumps, deaerator, deaerator evaporation cooler, water-to-water and steam-to-water heat exchangers, turbo plant condenser, electric generator, gas cooler, continuous blow-down expander, ejector, mixing facility, heat consumers and power sources. The turbine is represented by the following equipment: valves, regulation stage, intermediate stage, final stage, exhaust, steam extraction facilities.

Block-diagram of the CAD system for designing heat supply circuits of boiler plants is shown in fig.1. In this block-diagram logic-numerical operators ∇F, ∇P, $\nabla \eta$, $\nabla \Pi$, ∇E define technical-economic indices, heat carriers flow rates, pressure in the elements of heat-supply circuit, turbine efficiency, enthalpy and engine power. Complex optimization of heat supply circuits and boiler house equipment should be performed in the following way: at the initial stage of investigation of heat power supply systems for industrial enterprises it is expedient to use the method of system analysis [5].

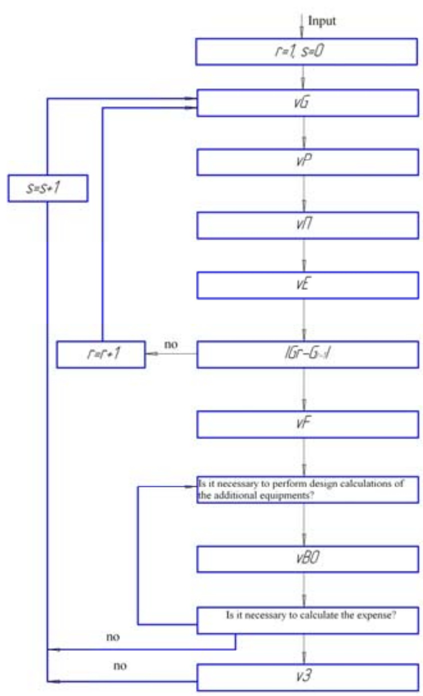

Fig. 1 – Block-diagram of the CAD system for designing heat-supply circuits

According to this method quality function of system F in the normalized form is given by

$$F(x_1, x_2, ..., x_n) = \sum_{i=1}^{n} k_i F_i(x_i), \qquad (6)$$

where n is a total number of parameters;

$F_i(x_i)(i = 1...n)$ – normalized one-dimensional utility functions;

k_i – weighting coefficients that characterize value relationships between individual criteria.

The method is restricted by the conditions of independence of criteria (X_i, X_j) $(i = 1...n-1, j = i+1...n)$ from other criteria.

Taking this into account, function $F(x_1, x_2, ..., x_n)$ is calculated in the following order:

1. Assignment of x_i criteria and their best and worst levels;
2. Determining independence of x_i criteria according to their advantages;
3. Defining one-dimensional functions $F_i(x_i)$;
4. Finding weighting coefficients k_i;
5. Calculation of $F(x_1, x_2, ..., x_n)$.

In order to check independence it is necessary to find such cases, where the structure of expert advantages violates the assumption of independence. If such cases are absent, conditions of independence are satisfied. If such cases are present, criteria should be changed. Defining of one-dimensional functions $F_i(x_i)$, performed by the expert, is realized in a graphic form (fig. 2.). For each parameter the worst and the best of its values are given. The value of one-dimensional function, equal to zero, corresponds to the value of $x_i = x_i^{worst}$ and the value, equal to 1, corresponds to the value of $x_i = x_i^{best}$, i.e.

$$F_i(x_i) = \begin{matrix} 0, x_i = x^{wast} \\ 1, x_i = x^{best} \end{matrix} \qquad (7)$$

The third point is found on the plot by a random choice. It is necessary to find such determinated equivalent that its utility $F_i(x_i^{\det erm})$ would be equal to the expected one:

$$F_i(x_i^{\det erm.}) = 0{,}5F_i(x_i^{worst}) + 0{,}5F_i(x_i^{best}) = 0{,}5 \qquad (8)$$

The plots are approximated by parabolic functions. Weighting coefficients are evaluated in two steps: first they are ranged according to their importance and then their numerical values are determined. This is done by establishing value relationships between the criteria. These relationships determine possible changes of some criteria at the expense of others. Evaluation of coefficients is the same as their evaluation when one-dimensional functions are plotted with direct participation of the expert.

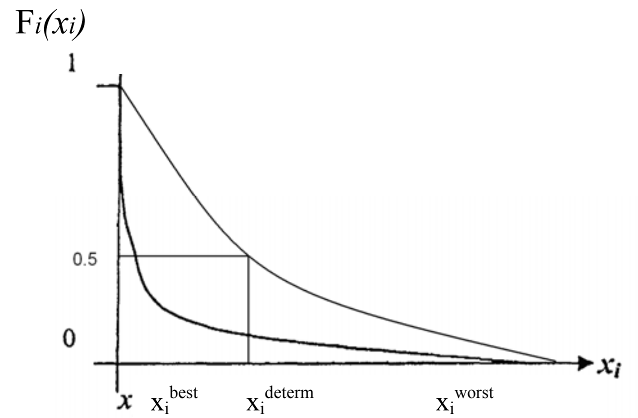

Fig.2 Construction of one-dimensional utility functions

Now, that we have the value of coefficients k_i and know what form one-dimensional functions $F_i(x_i)$ have, the value of multiple function $F(x_1, x_2, \ldots, x_n)$ can be found.

At the second stage synthesis of the boiler house scheme is performed, i.e. minimum $З_\Sigma$ is found as a result of its structures and parameters optimization. Here structure means boiler house scheme with definite number of elements, their technological functions and means of their interconnection. Structure optimization is conducted by choosing possible Г structures from the list. Optimization of parameters X, with the uncertainty of initial information $\Lambda_в$ being taken into account, is performed in the following way. Parameters of the boiler plant equipment can be divided into external and internal ones. The external parameters include the parameters of energy carriers at the inputs and outputs of the equipment. Under the internal parameters of the element its design parameters are meant.

When external parameters are optimized, the uncertainty is being reduced in the following way. Using expert estimates, the range of changes in specific cost parameters and other technical and economic indices is determined, alternative sets of these indices are formed (optimistic, average, pessimistic). Then optimization of boiler plants is conducted for each set of indices. Furthermore, stability of the obtained optimal parameters to the changes of initial information is investigated and from engineering considerations the final variant of the boiler house scheme parameters is chosen.

The proposed strategy for complex optimization of boiler houses was validated on the problems of choosing the configuration of heat-power supply system for the enterprises with thermal power of 30 Mw and for modernization of the boiler house of oil-extraction enterprise.

In the first case an expedient combination of the possible sources of thermal and electric energy was determined. The following thermal power sources were adopted as possible ones: hot-water boilers – WB, steam boilers – SB, heat pump unit – HPU. The possible electric energy sources: STP – steam-turbine plant, GTP – gas-turbine plant, GPE – gas-piston engine. The adopted criteria for the variants of energy supply sources are given in Table 1.

Table 1

Criteria for the variants of energy supply sources

Criteria	Best level	Worst level
X1 – Probability of accidents, 10^{-5}	50	80
X2 – Probability of fires and explosions, 10^{-7}	200	600
X3 – Dependence on external sources, points	0	100
X4 – Fuel costs, mln. hrn./year	20,53	26,45
X5 – Costs of energy supply from external consumers, mln. hrn./year	0	4,788
X6 – Capital investments, mln. hrn	3,070	7,715
X7 – Emissions of CO_2, SO_2, NO_2, tons / year	358,8	500
X8 – Salary, mln. hrn./year	0,4	0,6
X9 – Probability of failures, points	0	100
X10 – Level of negative influence on the personnel, points	0	100
X11 – Water costs, mln. hrn./ year	0,25	0,5
X12 – Repair costs, mln. hrn./ year	0,6	1
X13 – Construction costs, mln. hrn.	40	50
X14 – Receipts from electric energy sales, mln. hrn./year	1,25	0

Nine variants were considered :

Variant 1. Basic variant; variant 2. SB, WB and STP; variant 3. SB and GTP; variant 4. SB and STP; variant 5. SB, WB, GPE; variant 6. SB, WB and GTP; variant 7. SB, HPU, WB, GTP and STP; variant 8. SB, WB and HPU.

The variant with steam boiler was adopted as a basic one. The most significant calculation results are given in Table 2.

Table 2

Results of the heat-power supply system calculations

Criteria	SB		SB+WB+STP		SB+GPE		SB+STP	
Receipts from electric energy sales, mln.hrn. /year	0	0	1,25	$5,01*10^{-1}$	0	0	1,25	$5,01*10^{-1}$
Costs of electric energy from external sources, mln. hrn./ year	0,45	$2,2*10^{-1}$	0	$2,76*10^{-1}$	0	$2,76*10^{-1}$	0	$2,76*10^{-1}$
Fuel costs, mln. hrn./ year	25,6	$127*10^{-2}$	21,43	$9,26*10^{-2}$	25,85	$8,95*10^{-3}$	25,6	$1,26*10^{-2}$
Capital investments, mln. hrn./ year	3,76	$4,75*10^{-2}$	4	$4,24*10^{-2}$	3,83	$4,6*10^{-2}$	4,76	$2,8*10^{-2}$
Construction costs, mln. hrn./ year	40	$1,1*10^{-3}$	41,5	$7,766*10^{-3}$	40,2	$1,05*10^{-2}$	40,2	$1,05*10^{-2}$
Probability of failures, %	0	$8,56*10^{-3}$	28	$4,17*10^{-3}$	25	$4,48*10^{-3}$	20	$5,29*10^{-3}$
Repair costs, mln. hrn./ year	0,6	$4,9*10^{-3}$	0,75	$2,055*10^{-3}$	0,7	$2,5*10^{-3}$	0,65	$3,7*10^{-3}$
Emissions of CO_2, SO_2, NO_2, tons / year	493	$6,37*10^{-5}$	363,7	$2,949*10^{-3}$	500	0	493	$6,37*10^{-5}$
Dependence on external sources, %	100	0	0	$1,18*10^{-3}$	0	$1,18*10^{-3}$	0	$1,18*10^{-3}$
Water costs, mln. hrn./ year	0,25	$1,04*10^{-3}$	0,25	$1,045*10^{-3}$	0,25	$1,04*10^{-3}$	0,25	$1,044*10^{-3}$
Salary, mln. hrn./ year	0,4	$4,15*10^{-4}$	0,435	$3,194*10^{-4}$	0,43	$3,32*10^{-4}$	0,44	$3,065*10^{-4}$
Probability of fires, explosions 10^{-7}, %	200	$2,47*10^{-4}$	350	$1,297*10^{-4}$	280	$1,81*10^{-4}$	320	$1,51*10^{-4}$
Level of negative influence on the personnel, %	0	$2,27*10^{-4}$	40	$8,77*10^{-5}$	60	$5,85*10^{-5}$	35	$9,5*10^{-5}$
Probability of accidents, 10^{-5}, %	50	$7,98*10^{-5}$	63	$3,22*10^{-5}$	55	$5,92*10^{-5}$	57	$5,17*10^{-5}$
Utility functions	0,3065		0,932		0,352		0,841	

The following variants are considered to be the best ones: hot-water boiler house and steam turbine with total utility function 0, 93, steam boiler house with similar turbine having total utility function 0, 84 and the combination of hot-water boiler house with a heat pump unit.

The last variant is rather complicated as to its implementation, although it provides a 25% reduction of fuel consumption as compared to the existing variant. The variant with steam- and hot-water boilers and a steam turbine has the highest index because of the high criteria values connected with the receipts from the electric energy sales, fuel costs and total capital investments.

The variant with steam boilers and a steam turbine has a bit higher fuel expenses but lower construction and repair costs as well as lower probability of accidents. Therefore, the variant with steam boilers and a steam turbine has been considered to be the most expedient final choice. Then the optimal structure and parameters of the boiler house heat-supply circuit with steam generator for burning hull and gas was determined.

The initial scheme includes two boilers E-16-39/380 and KE-10-14/25 that consume 91 tons of hull per day. As the enterprise will be expanded, it is planned to increase the amount of hull consumption to 250 tons per day. For the hull utilization, it is planned to install two boilers E-16-39/360 and E-25-39/360 according the project of “ENERGOMASHPROJEKT” special design bureau.

In order to choose equipment of the boiler house being modernized, it is expedient to consider the variants of the heat-supply circuits without turbines, with a back-pressure turbine and with a condensing turbine. According to the quality criteria of the circuit variant, the total equipment costs can be adopted. Some initial data are non-determinated due to the uncertainty of their changes in the course of exploitation. Taking this into account, alternative arrays of input data were formed (Table 3).

Table 3

Alternative arrays of initial data

Parameters	Alternative variants		
	Pessimistic	Average	Optimistic
Fuel cost, 1 ton, hrn.	50	5	3
Electric energy cost, 1 kW, hrn	100	45	35
Heat energy cost, 1 hectocal, hrn	400	300	200

Calculation results for the heat-supply circuit variants without turbines and with the turbines for the average alternative input data array are given in Table 4.

Table 4

Results of the heat-supply circuit calculations

Circuit variants	Turbine power Ne, kw	Thermal power Q, hectocal.	Difference between the specific total costs, mln. hrn./year
Basic	0	27,45	0
With back-pressure turbine	2,6	26,405	- 5,303
With condensing turbine	6,8	15,26	- 7,898

In accordance with the calculations, heat-power circuit with ST turbine has the best indices. Quality graph is shown in fig.3.

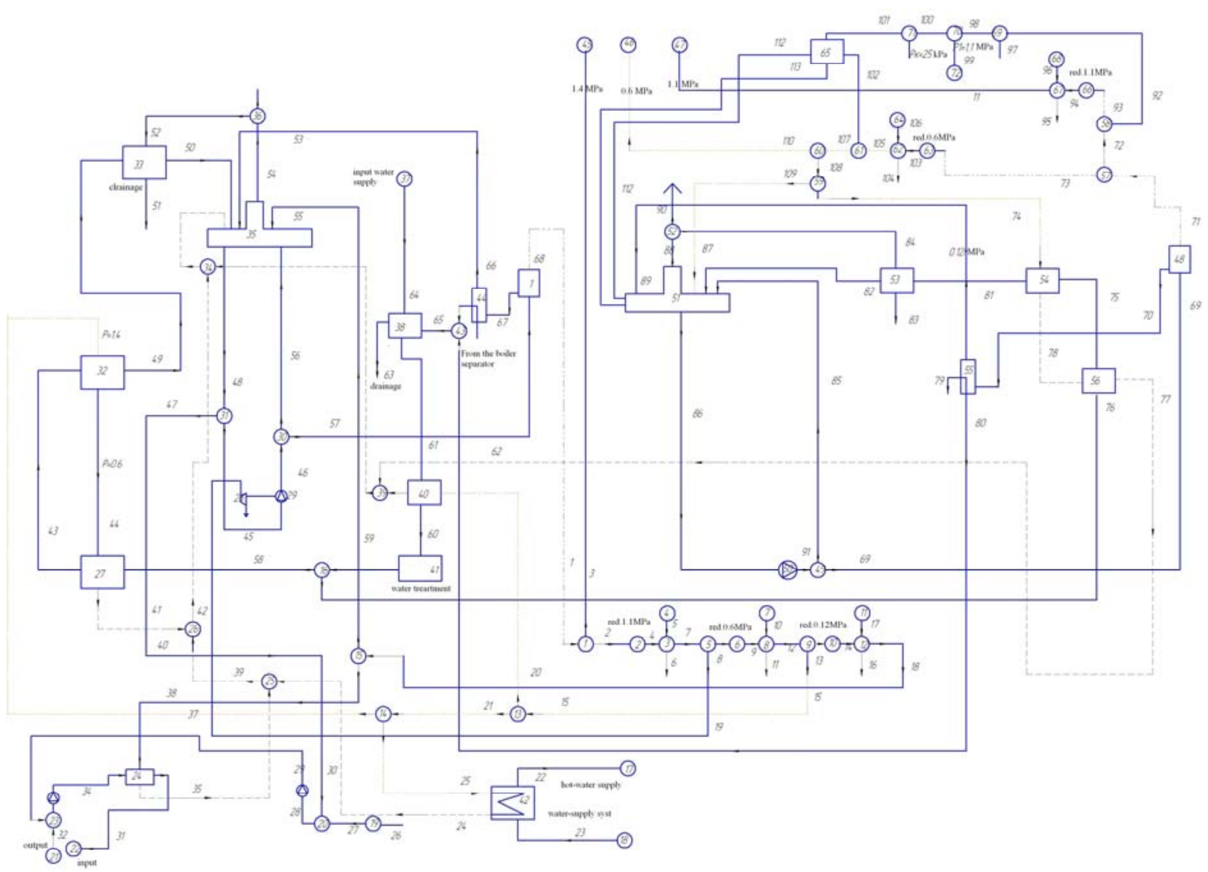

Fig. 3. Graph of the heat -supply circuit for industrial boiler house

This circuit includes condensing plant, the parameters of which it is expedient to optimize. The following optimization parameters were adopted: n_p – number of pipes, G_{cw} – cooling water flow rate, L_p – length of the pipes and d_p – external diameter of the pipe. Characteristics of the initial and optimal variants are presented in table 5.

Table 5

Optimization results for the 50% operation mode

Variants	n_p, items	G_{cw}, kg/s	L_p, m	d_p, mm	$\Delta З_{\Sigma}$, thousand hrn.
Initial	950	1400	4	14	0
Optimal	1220	3400	4,44	16	159,4

The optimization results show that it is expedient to adopt the cooling water flow rate 1220 kg/s and the number of pumps – 3400. The calculations were performed for the average alternative array of initial data. The calculations for other data arrays have given practically the same results, i.e. the assigned optimization parameters are stable to the changes of initial information.

Conclusions

1. The known method for mathematical modeling of heat power plants has been developed in the direction of mathematical modeling of industrial boiler houses and thermal power ministations.

2. CAD system has been developed for designing heat-supply circuits of the boiler house and heat power ministration, which makes it possible to perform their structural and numerical optimization.

3. The optimization calculations of the industrial boiler house have shown that it is expedient to install a turbine with a redesigned condensing plant.

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