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DIGITAL MODELS OF STABILIZING THE HYDRAULIC MODE OF HEAT SUPPLY SYSTEMS

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ABSTRACT

This article presents a method and algorithm for solving the problem of stabilizing the hydraulic modes of a heat supply system main fragments based on setting the threshold values of control valves for flow and pressure regulators used in the field of technological processes automated control of the system and using a two-level decomposition of the heat supply system. Research has been carried out to confirm the software computational efficiency of the developed models and algorithms. In the course of this study, models for stabilization of the hydraulic mode by distribution fragments of a heating network were not considered. As a rule, include nodes of connection to main networks a distribution pipeline network with a pipeline diameter of less than 400 mm, step-down and booster pumping stations, respectively, on the opposite and supply pipelines or mixing pumping stations between supply and return pipelines, individual heat points of consumers with dissimilar heat consumption loads. The development of permissible modes of all distribution fragments is the second stage in the search for an admissible mode of a large heat supply system after the search for an admissible mode of the main system fragment is completed.

Keywords: *Heat Supply System, Decomposition, Hydraulic Control, Stabilization, Method, Algorithm, Software Implementation, Efficiency.*

1. INTRODUCTION

In the areas of adjusting the heat supply systems of metropolises (HSSM), the functions of developing permissible steady-state hydraulic modes in systems with throttling regulating bodies (direct acting automatic flow controllers (FC) and pressure controllers (PC)) are still remain actual and labor intensive [1-6].

The basis for the creation and development of urban infrastructure is the solution to the problem of dynamic planning of the Smart City [7-10].

Evaluation of the operability and computational efficiency of algorithms for solving problems on systems of nonlinear equations with arbitrary nonlinearities, to which the problem of stabilizing the parameters of the hydraulic mode of main fragments of HSSM belongs is practically impossible, therefore, the only way to evaluate them is their posterior estimations after the corresponding software implementation [11], [12].

To create a software technology for modeling the stabilization of hydraulic modes based on algorithms for solving problems on nonlinear equations systems with arbitrary nonlinearities and then assessing their effectiveness, it is necessary to develop a digital model for solving the problem of stabilizing the hydraulic mode of the FCM, which includes solution of the following problems:

– the synthesis task's formalization for permissible hydraulic mode of the heat supply systems' main fragments;

– determination of admissible values' range for the parameters of the hydraulic mode based on the conditions of normal operation by all objects of the heat supply system;

– development of a mathematical model for a formalized problem of the synthesis of an admissible hydraulic mode by main fragments using a two-level decomposition;

– development of an algorithm for solving the problem of finding a stabilized hydraulic mode based on the decomposition of a large heat supply system into parts and the linearization of the selected parts;

– evaluation of the computational efficiency of the developed digital model of stabilization for the parameters of the hydraulic mode by main fragments in the course of their software implementation.

Subsequently, outcome of the first models analysis of iterative processes for hydraulic resistances of control valves by flow and pressure controllers [5, 9-10, 14], drawbacks were identified, For instance, the models of flow and pressure controllers were represented by models of astatic indirect controllers performance. Moreover, the set value of the controlled variable was provided by the position regulating body, which, in principle, did not reflect the process of real FCs performance and pressure controllers of direct action. To solve this drawback, a general scheme of the method for solving the problem of searching for an admissible hydraulic mode was developed, based on the fact that in real heating networks, the points of selection of signals of controlled quantities may not coincide with the areas where the control valves are located.

As a result of the research, a fundamentally new approach to solving the problems of managing the heat supplying power systems production is proposed, It is the development of an automated control system for the transmission and distribution of heat energy by changing the throughput of the heat network which created on the basis of the developed digital model and using a two-level decomposition of the heat supply system.

2. DIGITAL MODEL FOR SOLVING THE PROBLEM OF STABILIZING THE HYDRAULIC CONTROL OF THE HSSM USING A TWO-LEVEL DECOMPOSITION.

The preset values of the stabilized flow rates (FC setpoints) and pressures (PC setpoints) must satisfy the known technological limitations on the mode parameters, which determine the permissible mode.

As a rule, the main section of the HSSM includes heat supply sources, a main pipeline network with a pipeline diameter of more than 500 mm, network pumping stations, control and distribution and central heating points, nodes for connecting loaded branches, i.e. distribution networks.

Let us formalize the problem of synthesizing the permissible hydraulic control of main HSSM fragments as follows:

preset:

- nodes of fixed technological structure of HSSM;
- passive sections of the pipeline network and their design and hydraulic parameters;
- active sections (pumping modules) and their pressure-flow characteristics for all operating pumping stations;
- the place of installation and hydraulic characteristics of all throttle control valves (TCV) of automatic flow and pressure controllers, which ensure the stabilization of flow rates at specified sections and pressures at specified nodes;
- the place of installation and hydraulic characteristics of all throttle control valves of automatic flow and pressure regulators, ensuring the stabilization of flow rates at specified sections and pressures at specified nodes;
- process chart of system consumers and their mass loads for all types of heat consumption;
- preset ranges of stabilized flow rates preferred values and pressures of the energy carrier, which determine the permissible hydraulic mode;

need to define:

- mass flow rates of the energy carrier in the sections and pressure in the nodes of the HSSM pipeline network;
- modes of pumping stations and TCV where the steady-state values of the stabilized mode parameters fall within the specified intervals of technologically permissible values.

The problem consists in determining the parameters of the required hydraulic mode or the parameters of the hydraulic mode, which is the best approximation to the required mode if the latter is not feasible with the initial state of the system and the initial settings of the FC and PC (figure 1).

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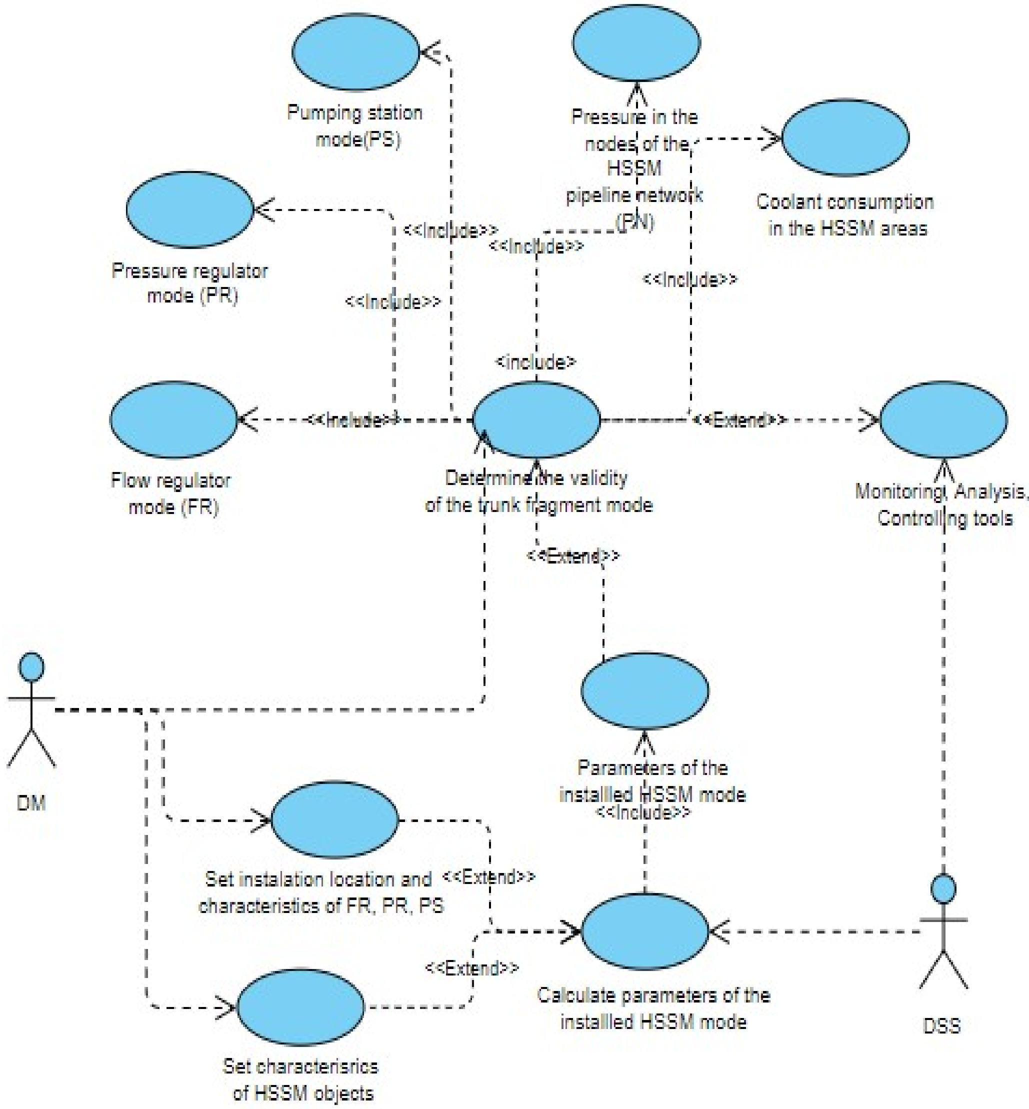

Figure 1. Formalization of the problem of the main HSSM fragments hydraulic control parameters stabilization

Since the settings of the FC and PC in heat supply systems with automatic stabilization of the mode parameters determine the permissible hydraulic mode, the formulated problem allows one to determine such settings for the existing FC and PC that would meet technological constraints and would be physically feasible in systems with a given technological structure and fixed parameters of active and passive technological elements.

Consequently, the area of admissible values of the parameters of the hydraulic control is formed from the conditions of all objects normal operation of the heat supply system.

The upper maximum permissible piezometric pressure P^{+} for the nodes of the supply pipelines is assigned from the condition of the mechanical strength of the heat supply sources technological equipment, pipelines and fittings of supply lines, pumping stations and consumers. For real thermal mechanical equipment of heat supply sources $P^{+}=$ 2.5 MPa (250 mWC), for pipelines and valves of the heating network $P^{+}=$ 1.6 MPa (160 mWC) and for consumers with a dependent connection scheme $P^{+}=$ 0.6 MPa (60 mWC).

The lower maximum permissible piezometric pressure P^{-} for the nodes of the supply pipelines is assigned from the condition of protection against non-boiling of the energy carrier. At a design temperature of the energy carrier 150°C in the supply pipelines at the exit from the heat supply source, the non-boiling pressure is $P^{-} = 0.38$ MPa (38 mWC), at a temperature of 180°C $P^{-} = 0.9$ MPa (90 mWC).

The upper maximum permissible piezometric pressure P^{+} for the return pipelines is assigned from the condition of the mechanical strength of consumers' heat-mechanical equipment of with a dependent connection scheme or water-to-water heaters with an independent connection scheme of consumers. For consumers with dependent connection $P^{+} = 0.6$ MPa (60 m.w.st), and for consumers with independent connection $P^{+} = 1$ MPa (100 m.w.st).

The lower maximum permissible piezometric pressure for the nodes of return pipelines is assigned from the condition of vacuum prevention in pipelines and cavitation at the pump inlet $P^{+} =$ 0.05-0.1 MPa (5-10 mWC).

The area of permissible values of total pressures in the nodes of the supply pipelines for each hydraulic zone of the pipeline network of the system, distributed in space, is determined separately by the following ratio $P_{ij} > P_{cj}^{+}$, where P_{ij} is the total pressure in the i^{th} node of the supply pipeline in the j^{th} hydraulic zone; P_{cj}^{+} is the permissible static pressure in the j^{th} zone, which is determined based on the mechanical strength of the thermal-mechanical equipment installed in the node of the heat supply system with the lowest geodetic mark.

The area of admissible flow rates in areas with flow stabilization with the help of automatic controllers is determined by their accuracy characteristics and the controllability area of the used TCV.

Let's create a mathematical model of the formulated problem based on the idea of a large heat supply system decomposition into parts and the method of the selected parts linearization. Then divide the design scheme of the original large hydraulic circuit into a connected basic subsystem with one component of connectivity (Figure 2) (nodes for connecting heat supply sources and a node with a given system pressure are located in the basic subsystem) and a fixed number of selected subsystems, removing m1 sections with TCV from the original design scheme flow controllers and m2 pressure controllers.

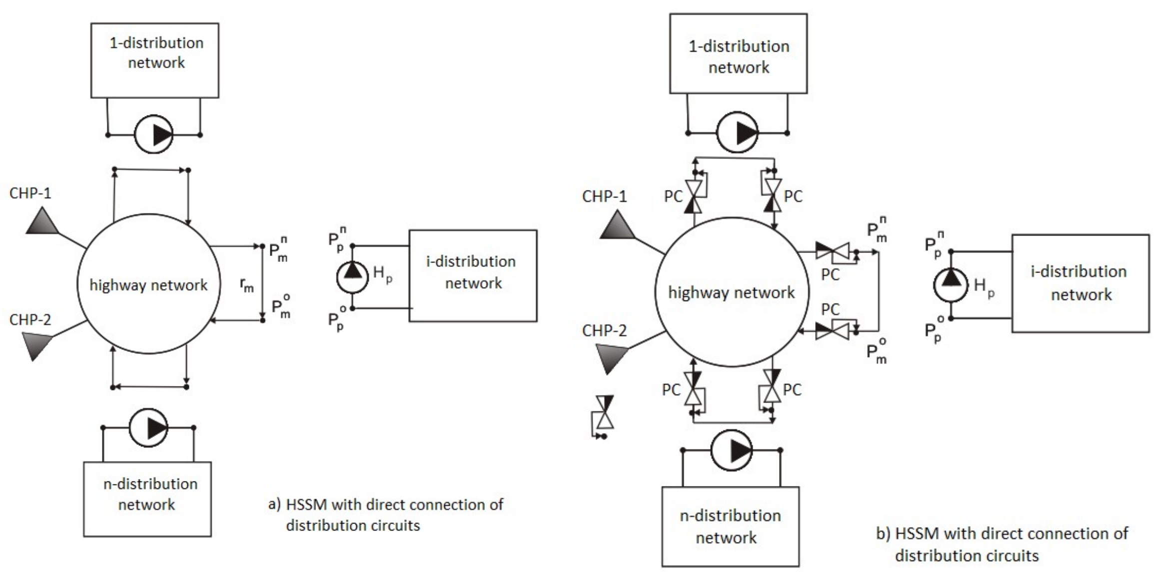

Figure 2. Decomposition of the TCM hydraulic circuit with fixed consumer resistances

Then the structure of the basic subsystem will be displayed by a directed connected graph *G(M,N)* over the set *M* of its nodes and *N* arcs (sections), and the structure of each selected subsystem will be

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represented by a pair of nodes and a branch with variable hydraulic resistance connecting them.

To describe the connections between the base and selected subsystems, let us introduce $2\cdot(m_1+m_2)$ additional variables, such as the costs at the nodes of the TCV connection from the set *M*. Then the steady state of the base subsystem can be described by the following equations:

$$\sum_{i=1}^{n} a_{ji}\cdot x_i - \hat{q}_j = 0,\quad j \equiv \overline{1,\ m-1}, \tag{1}$$

$$\sum_{j=1}^{m} \hat{q}_j = 0, \tag{2}$$

$$\varphi_i(x_i) + \sum_{s=k+1}^{n} b_{is}\cdot\varphi_s(x_s) = 0 \quad i = \overline{1,k}, \tag{3}$$

$$\varphi_i(x_i) = \sum_{s=1}^{m} a^{g}{}_{is}\cdot p_s,\quad i = \overline{1,n}, \tag{4}$$

$$\hat{q}_j = Q_j + \sum_{i=1}^{m_1+m_2} q_i\cdot(\delta_{ij1} - \delta_{ij0}),\ j = \overline{1,m}. \tag{5}$$

The steady state of the selected subsystems is displayed by the equations:

$$p_{i0} - p_{i1} - \psi_i(q_i) = 0,\ \ i = 1,\ \ m_1 + m_2 \tag{6}$$

In this case, use the following values of the variables:

k – the number of independent contours and nodes on the graph $G(M,N)$; $n = |N|$ – number of regions on the graph $G(M,N)$; $m = |M|$ – the number of nodes on the graph $G(M,N)$;

$x = (x', x'')$ – vector of mass flow on the branches of the graph *G*; $x' = (x_1,\ldots,x_k)$, $x'' = (x_{k+1},\ldots,x_n)$ – respectively, the vectors of mass flow rates on the chords and branches of the spanning tree selected on the graph *G*;

$\hat{q} = (\hat{q}_1,\ldots,\hat{q}_m)$ – vector of nodal mass flow rates of the energy carrier, reflecting the mass exchange of the base subsystem with the environment after the equivalent separation of significant nonlinearities;

Q_j, $j = \overline{1,m}$ – massive inflow or load of the energy carrier at the network nodes; $q = (q', q'')$ – vector of mass consumption of energy carrier through the TCV of the selected subsystems;

$q' = (q_1,\ldots,q_{m_1})$ – vector of mass flow rates through the TCV of the corresponding flow controllers;

$q'' = (q_{m_1+1},\ldots,q_{m_1+m_2})$ – vector of mass flow rates through the TCV of the corresponding pressure controllers;

$p = (p', p'')$ – vector of total pressures at the nodes of the base subsystem; $p' = (p_1,\ldots,q_{m_2})$ – vector of total pressures in nodes with pressure stabilization; $p'' = (p_{m_2+1},\ldots,q_m)$ – vector of total pressures in nodes without pressure stabilization; $p_m = const$ – preset pressure in the support node of the system;

$\{b_{is}\}$, $i = \overline{1,k}$, $s = \overline{1,n}$ – matrix of independent contours on the graph of the base subsystem G;

$\{a_{ij}\}$, $i = \overline{1,n}$, $j = \overline{1,m-1}$ – matrix of connections of linearly independent nodes on a graph G;

$\{a^{g}{}_{is}\}$, $i = \overline{1,m-1}$, $s = \overline{1,m}$ – transposed matrix of connections on a spanning tree of a graph G;

δ_{ij} – Kronecker symbol; i_0 – starting node of i^{th} region; i_1 – ending node i^{th} region;

$\varphi_i(x_i)$, $i = \overline{1,n}$ – pressure loss in the sections of the basic subsystem; $\psi_i(q_i)$, $i = \overline{1,m_1+m_2}$ – pressure loss on the TCV of flow and pressure controllers;

The system of equations (1) reflects the first network Kirchhoff's law that for any flow distribution in each *j* node a balance must be observed that corresponds to the principle of flow continuity. That is, the algebraic sum $\sum_{i=1}^{n} a_{ji}x_i$ of expenditures for all branches having a common (regardless of whether it is the final or initial) *j* node should be equal to the expenditure $\hat{q}_j$ in this node. In this case, system (2) expresses mathematically the general zero balance $\hat{q}_j$ of costs for all m nodes of the circuit.

Each of the equations of system (5) expresses the mass consumption of the energy carrier $\hat{q}_j$ in the i^{th} node, reflecting the mass exchange of the base subsystem with the environment, through the sum of the mass inflow or load of the energy carrier in this node and the mass consumption of the energy carrier through the TCV of the selected subsystems.

Each of the equations of system (3) reflects the second network Kirchhoff's law, which says about the total zero change in pressure drops $\varphi_i(x_i)$ (in i sections) in any circuit of the circuit. In this case, there will be only k linearly independent equations (according to the number of independent contours of the entire system).

Each equation of system (4) determines the pressure drop $\varphi_i(x_i)$ at each section i through the total pressures at the nodes of the base system. Indeed, each i^{th} column of the matrix $\{a_{ij}\}, i=\overline{1,n},\ j=\overline{1,m-1}$ contains information (in the form of two numbers: 1 and -1 in the corresponding places j_1 and j_2) not only about the end nodes of this branch, but also about its orientation. When transposed, the columns of the matrix $\{a_{ij}\}, i=\overline{1,n},\ j=\overline{1,m-1}$ change with the rows, and as a result of further multiplication of the transposed matrix $\{a^g{}_{is}\}, i=\overline{1,m-1},\ s=\overline{1,m}$ by the column vector of total pressures at the nodes of the system, we get just the pressure drop $\varphi_i(x_i)=p_0-p_1$, where p_0 is the pressure at the node located at the beginning of section i; p_1 - pressure in the node located at the end of section i.

Each of the equations of system (6) takes into account the presence of flow and pressure regulators at the i^{th} section of pressure losses in the TCV. Thus, the total pressures at the nodes will depend on the equations of system (6). There will be such m_1+m_2 equations - by the number of sections with TCV FC and PC.

Thus, the system of equations was obtained (1)–(6) that was consistent for physical reasons.

Dependence $\varphi_i(x_i)$ for active sections (pumping modules) of the basic subsystem has the form:

$$\varphi_i(x_i)=r_{0i}+r_{1i}\cdot x_i+r_{2i}\cdot x_i^2,\quad i=\overline{1,} \tag{7}$$

where r_{0i}, r_{1i}, r_{2i} are hydraulic constants of the pressure-flow characteristic of the i^{th} pump module at a constant speed of the impeller;

n_1 – the number of active sections (pumping modules) in the basic subsystem.

For passive sections, the dependence $\varphi_i(x_i)$ has the form:

$$\varphi_i(\mathrm{x}_i)=r_{3i}\cdot|x_i|^{\alpha_i}\,sign(x_i),\quad i=\overline{n_1+1} \tag{8}$$

where r_{3i} – hydraulic resistance of the i^{th} passive section of the basic subsystem;

α_i – hydraulic constant of the i^{th} passive section of the base subsystem.

The pressure loss across the TCV of the flow and pressure regulators is approximated by the following expression:

$$\psi_i(\mathrm{x}_i)=r_i\cdot q_i^2 sign(q_i),\quad i=\overline{1,m_1+m_2}, \tag{9}$$

$$r_i\in\left[r_i^-;r_i^+\right],\quad i=\overline{1,m_1+m_2}, \tag{10}$$

where r_i – variable value representing the hydraulic resistance of the i^{th} TCV;

r_i^- – hydraulic resistance in the fully open position of the shutter of the i^{th} TCV valve controller;

r_i^+ – hydraulic resistance in the fully closed position of the valve regulator gate of the i^{th} TCV.

Suppose in network $q'=(q_1,\ldots,q_{m_1})$ is the vector of stabilized flow rates at given sections with TCV, $p'=(p_1,\ldots,q_{m_2})$ is the vector of total stabilized pressures at the nodes, wherein $m_1<n$, $m_2<m$. Therefore, i^{th} consumption controller ($i=\overline{1,m_1}$) stabilizes the flow in the i^{th}, and j^{th} pressure controller ($j=\overline{1,m_2}$) stabilizes the pressure in j^{th} node of network that may not belong to the border node of the TCV.

The problem consists in finding such values of r_i (the state of the TCV) at which the conditions for the stabilized parameters of the control q', p' would be satisfied:

$$q_i \in \left[q_i^-; q_i^+\right], \quad i = \overline{1, m_1}, \tag{11}$$

where q_i^- is the lower preset value of the stabilized flow through the TCV i^{th} flow controller;

q_i^+ – upper set value of the stabilized flow through the TCV i^{th} flow controller;

$$p_j \in \left[p_j^-; p_j^+\right], \quad j = \overline{1, m_2}, \tag{12}$$

where p_i^- is lower preset value of the stabilized pressure in the i^{th} node of the pipeline network;

p_i^+ – upper set value of the stabilized pressure in the i^{th} node of the pipeline network.

The admissible hydraulic mode of the HSSM in the space of stabilized flow rates and pressures (11), (12) will be determined by the point $(q', p') \in \Phi$, where Φ is admissible region corresponding to the system of equations (1) - (6) and closing dependencies (7) – (10).

Then the development of the required hydraulic regime is reduced to the problem of minimizing the $J(q', p')$ on the admissible set of Φ:

$$J(q', p') = \sum_{i=1}^{m_1} \Delta q_i + \sum_{j=1}^{m_2} \Delta p_j \to \min_{(q', p') \in \Phi} \tag{13}$$

,

where $\Delta q_i, \Delta p_j$ – positive definite functions of the relative deviations of the stabilized flow rates and total pressures from the set values;

$$\Delta q_i = \max\left\{\frac{q_i - q_i^+}{q_i^+}, \frac{q_i^- - q_i}{q_i^-}, 0\right\}, \quad i = \overline{1, m_1}, \tag{14}$$

$$\Delta p_j = \max\left\{\frac{p_j - p_j^+}{p_j^+}, \frac{p_j^- - p_j}{p_j^-}, 0\right\}, \quad j = \overline{1, m_2}. \tag{15}$$

Thus, the task of developing the required hydraulic control is formalized and reduced to a typical problem of nonlinear mathematical programming (1) - (15).

- if there are (q'^*, p'^*) that transform the equations of system (1) - (6) into identities under the closing relations (7) - (9) and at the same time constraints (10) - (12) are satisfied, then $\min\limits_{(q', p')} J(q'^*, p'^*) = 0$ and the required hydraulic regime of the HSSM exists for the initial values of parameters of technological elements and settings of FCs and PCs.

- if the roots of the system (q'^*, p'^*) (1) - (6) are inconsistent with the constraints (10) - (12), then the required hydraulic mode with the initial settings of the FC and PC does not exist for a given state of the passive and active elements of the HSSM.

To solve problem (1) - (13), we will use an effective numerical method based on recursive sequences $\{x^t\}$ for the mass consumption of the energy carrier in the sections of the basic system, as well as $\{q^l\}$ for the mass consumption of the energy carrier through the TCV.

Algorithms that generate the above sequences form a nested cyclic structure in which the $\{q^l\}$ is external and the $\{x^t\}$ is internal (nested) process.

The general scheme for solving the formulated problem of nonlinear mathematical programming can be constructed using effective flow distribution procedures for hydraulic circuits with variable parameters (due to controlled TCVs), based on the constructive idea of sequential linearization, which is based on the specific properties and structure of the systems of equations being solved.

The first models of iterative processes for the analysis of hydraulic resistance of control valves of flow and pressure regulators used in hydraulic circuits with controlled parameters were practically investigated in the automated system GID-99w [13], [14]. An analysis of the experience of the practical use of these models made it possible to establish their following shortcomings and the main ways to improve them:

- the mentioned iterative processes of the GID-99w system cannot be used in situations with flow reversal in the areas where they are installed and do not reflect the process of functioning of real direct-acting flow and pressure regulators, which are proportional regulators operating on the deviation of the controlled value from the set value. Rather, they are models of the functioning of indirect-acting astatic throttling regulators, in which the setpoint of the controlled variable can be provided at various positions of the regulating body, and the controlled variable is physically related to the area where the controlling valve is located;

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- regular use of the mentioned GID-99w processes in the digital control of stationary modes of complex heating networks is impossible due to the fact that the regulated pressures and costs physically belong to the network section where the control valves are installed, although in real heating networks the points of sampling of signals of controlled quantities may not coincide with the locations of the control valves.

The general scheme of the method for solving the problem of finding an admissible hydraulic regime including the above remarks is reduced to performing the following actions:

1) Arbitrarily determine the initial values of independent flow rates on the chords of the base subsystem $x_i^0 = const, \quad i = \overline{1,k}$.

2) Determine the initial values of the flow rate of the TCV of all FC $q_i^0 = \dfrac{q_i^+ + q_i^-}{2}, \quad i = \overline{1, m_1}$.

3) Determine the initial values of the flow rate of the TCV of all PC $q_i^0 = q_{yi}, \quad i = \overline{m_1 + 1, m_1 + m_2}$, where q_{yi} is the conditional throughput of the TCV -i^{th} PC, given in its technical specification.

4) Determine the initial values of the intermediate variables $MJ_1 = 1 \cdot 10^9$ and $MJ_2 = 1 \cdot 10^9$, which are subsequently used to find the minimum value of the functional $J(q', p')$.

5) The initial values of the dependent costs $\hat{q}^0_j, \quad i = \overline{1,m}$ are determined using (5):

- $\hat{q} = (\hat{q}_1, \ldots, \hat{q}_m)$ – vector of nodal mass flow rates of the energy carrier reflecting the mass transfer of the base subsystem with the environment;

- $Q_j \;, j = \overline{1,m}$ – massive inflow or load of the energy carrier at the network nodes;

- $q = (q', q'')$ – vector of mass consumption of energy carrier through the TCV of the selected subsystems;

- $q' = (q_1, \ldots, q_{m_1})$ – vector of mass flow rates through the TCV of the corresponding flow controllers;

- $q'' = (q_{m_1+1}, \ldots, q_{m_1+m_2})$ – vector of mass flow rates through the TCV of the corresponding pressure regulators.

6) The initial values of the dependent costs $x^0{}_s, \quad s = \overline{k+1, n}$ on the branches of the tree of the basic subsystem are determined using the linear system (1) at given $x^0{}_i, \quad i = \overline{1,k}$. As a result of solution (1), the vector $\hat{q}$ is transformed into $\tilde{q}$.

7) From the point x^0 at fixed $\tilde{q}$ using a recursive process $\{x^t\}$, the flow distribution $x^* = (x'^*, x''^*)$ on all branches of the graph of the base subsystem $G(M, N)$ is determined as an approximate value of the roots of systems (1) - (3).

The process $\{x^t\}$ can be described using equations (1) - (3) by the contour roots method (CRM). Recursive sequence takes the following form:

$$x_s^{t+1} = x_s^t + \Delta^t \cdot \delta_{sj}, \quad s = \overline{1,k}, j = \overline{1,k}, \tag{16}$$

$$x_s^{t+1} = x_s^t + \Delta^t \cdot b_{is} + \tilde{q}_s, \quad s = \overline{k+1, n}, \; t = 0,1,2,\ldots, \tag{17}$$

$$\Delta^t = \begin{cases} -E_i(x^t) + signE_i(x^t)\sqrt{E_i^2(x^t) + C_i(\cdot} \\ -E_i(x^t), \quad \text{при } E_i^2(x^t) \le C_i(x^t), \end{cases} \quad E_i^2(x^t) > C_i(x^t) \tag{18}$$

where $E_i(x^t) = \dfrac{\partial f_i(x^t)}{\partial x_i} \Big/ \dfrac{\partial^2 f_i(x^t)}{\partial x_i^2}$,

$C_i(x^t) = -2 f_i(x^t) \Big/ \dfrac{\partial^2 f_i(x^t)}{\partial x_i^2}, i = t \mod k+1;$

Δ^t – scalar correction to flow rates in sections, specifying the length of the i^{th} iteration step.

In (18) Δ^t is defined as the least modulus real root of the Taylor expansion of the i^{th} contour equation $f_i(x) = 0, \quad i = \overline{1,k}$,

$$f_i(x^t) + \frac{\partial f_i(x^t)}{\partial x_i} \cdot \Delta^t + \frac{1}{2} \cdot \frac{\partial^2 f_i(x^t)}{\partial x_i^2} \cdot \left(\Delta^t\right)^2 = \quad i = \overline{1,k} \tag{19}$$

or as the real part of the complex conjugate roots.

Relations (10) in general form define the recursive process of the CRM and make it possible to obtain constructive relationships for each specific class of pipeline systems

The process $\{x^t\}$ ends when the function W is true and continues otherwise:

$$W = \max_{1\le i\le k}\left|\Delta H_i\right| \le B_1 \wedge \max_{1\le s\le m}\left|\Delta Q_s\right| \le B \qquad (20)$$

where B_1, B_2 – specified permissible values, respectively, of the maximum absolute pressure discrepancy ΔH_i over a set of independent circuits and the absolute discrepancy of the flow rate balance ΔQ_s over a set of nodes.

The accumulation of round-off errors in the process $\{x^t\}$ leads to an increase in the nodal balance residuals across the set of nodes. Therefore, in the case of a false ratio $\max_{1\le s\le m}\left|\Delta Q_s\right| \le B_2$, the process is corrected using system (1), which is solved by an effective numerical method of moving along the tree of the basic subsystem.

8) With a known flow distribution $x^* = (x'^*, x''^*)$, system (18) is solved and the total pressures $p^* = (p'^*, p''^*)$ at the nodes of the G graph are determined.

9) New flow rates q_i^{l+1}, $i = \overline{1, m_1}$ are generated through the TCV of all flow controllers. If $y_i^{*l} = p_{i0}^{*l} - p_{i1}^{*l} > 0 \wedge r_i^{*l} = y_i^{*l} / \left(q_i^l\right)^2 \in \left[r_i^-; r_i^+\right]$, then $\Delta q_i^l = 0$ and $q_i^{l+1} = q_i^l$. If $y_i^{*l} > 0 \wedge r_i^{*l} \notin \left[r_i^-; r_i^+\right]$, then $q_i^l \notin \left[q_i^-; q_i^+\right]$, $\Delta q_i^l \ne 0$. Therefore:

$$q_i^{l+1} = \begin{cases} \sqrt{y_i^{*l} / r_i^-}, & npu\ r_i^{*l} < r_i^-, \\ \sqrt{y_i^{*l} / r_i^+}, & npu\ r_i^{*l} > r_i^+. \end{cases} \qquad (21)$$

If $y_i^{*l} < 0$, then $q_i^l \notin \left[q_i^-; q_i^+\right]$ and $\Delta q_i^l \ne 0$. Consequently, $q_i^{l+1} = q_i^l - \sqrt{\left|y_i^{*l}\right| / r_i^-}$.

The component of the functional is calculated by the accumulation method J:

$$J_1\left(q'^l, p'^l\right) = \sum_{i=1}^{m_1} \Delta q_i^l. \qquad (22)$$

If $J_1\left(q'^l, p'^l\right) < MJ_1$, then $MJ_1 = J_1\left(q'^l, p'^l\right)$ and $(Mq)_i = q_i^l$, where $(Mq)_i$ is an intermediate variable for maintaining the flow rate through the DRC of the th PP, corresponding to the minimum value of J_1 at the l^{th} iteration. Otherwise, the values of the variables MJ_1 and $(Mq)_i$ remain unchanged.

10) Cost values are generated q_i^{l+1}, $i = \overline{m_1 + 1, m_1 + m_2}$, through TCV of all PCs. If $y_i^{*l} > 0 \wedge r_i^{*l} \in \left[r_i^-; r_i^+\right] \wedge p_j^{*l} \in \left[p_j^-; p_j^+\right]$, $1 \le j \le m_2$ then $\Delta p_j^l = 0$ and $q_i^{l+1} = q_i^l$. If $y_i^{*l} > 0 \wedge r_i^{*l} \in \left[r_i^-; r_i^+\right] \wedge p_j^{*l} \notin \left[p_j^-; p_j^+\right]$, $1 \le j \le m_2$ then $\Delta p_j^l \ne 0$ and

$$q_i^{l+1} = q_i^l + sign\left(\frac{p_j^{*l} - p_j^{*(l-1)}}{q_i^l - q_i^{l-1}}\right)\Delta q_i^l.$$ There:

$$\Delta q_i^l = \begin{cases} \sqrt{\left(p_j^{*l} - p_j^+\right)/r_i^{*l}}, & p_j^{*l} > p_j^+ \wedge r \\ -\sqrt{\left(p_j^- - p_j^{*l}\right)/r_i^{*l}}, & p_j^{*l} < p_j^- \wedge \end{cases} \qquad (23)$$

If $y_i^{*l} > 0 \wedge r_i^{*l} \notin \left[r_i^-; r_i^+\right]$, then $\Delta p_j^l \ne 0$ and $q_i^{l+1} = q_i^l - \sqrt{\left|y_i^{*l}\right| / r_i^-}$.

The component of the functional is calculated by the accumulation method J:

$$J_2\left(q'^l, p'^l\right) = \sum_{j=1}^{m_2} \Delta p_j^l. \qquad (24)$$

If $J_2\left(q'^l, p'^l\right) < MJ_2$, then $MJ_2 = J_2\left(q'^l, p'^l\right)$ and $(Mq)_i = q_i^l$, $MJ^l = MJ_1 + MJ_2$, where $(Mq)_i$ – an intermediate variable for maintaining the flow rate through the DRC of the i^{th} PC corresponding to the minimum value J_2 at the l^{th} iteration. If $MJ^l = 0$, then the parameters $\{x^{*l}, p^{*l}, r^{*l}\}$ obtained during l iterations of the external process $\{q^l\}$ correspond

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to the required hydraulic mode with the initial settings FC and PC.

11) Actions 4-10 are repeated L times (L is the number of a priori given repetitions of the external process $\{q^l\}$).

Before the next repetition of steps 4-10, the initial values of the variables are updated $q_i^0 = q_i^{l+1}$, $i = \overline{1, m_1 + m_2}$; $x_i^0 = x_i^{l+1}$, $i = \overline{1,k}$. After the completion of the L^{th} iteration, the variable MJ^l is analyzed, where the minimum value of the functional J for the L iterations has been preserved.

If $MJ^l \neq 0$, then the parameters of the required hydraulic mode are not achieved, therefore the pragmatic value is determined by the parameters of the hydraulic mode, which is the best approximation to the required one. To obtain such parameters, the following actions are performed:

$$\begin{aligned} q_i^0 &= (Mq)_i, \; i = \overline{1, m_1 + m_2}, \\ x_i^0 &= x_i^L, \; i = \overline{1,k}, \end{aligned} \tag{25}$$

The initial values of the dependent costs $\hat{q}_j\left(j = \overline{1,m}\right)$ and $x_i^0\left(i = \overline{k+1,n}\right)$ are determined using (1) and (5) and the corresponding vector $\tilde{q}$ using the linear system (1). From the point x^0 at fixed $\tilde{q}$ using a recursive process $\{x^t\}$, the flow distribution $\hat{x}^{*(L)}$ on all branches of the graph of the base subsystem G is determined as an approximate solution of systems (15) - (17). Using (18), the total pressures at the nodes $\hat{x}^{*(L)}$ of the G graph are determined.

The parameters $\{x^{*(L)}, p^{*(L)}, r^{*(L)}\}$ represent the hydraulic duty, which is the best approximation to $\min J(q', p')$ the required duty with the initial FC and PC setpoints. The control analyst (DM) who develops the control mode can evaluate the control mode $\{x^{*(L)}, p^{*(L)}, r^{*(L)}\}$ according to a number of informal criteria reflecting his professional experience and decide to complete the modeling of the initial regime situation or to continue research with a large number of repetitions of the external cycle.

If during the l^{th} iteration at the modeling $MJ^l = 0 = \min J(q', p')$ step (k), then the parameters obtained in l iterations of the external process $\{q^l\}$ correspond to the required hydraulic mode with the initial settings FC and PC. The simulation of the initial regime situation is completed by obtaining the desired technical result.

The algorithm for solving the problem of finding an admissible stabilizing hydraulic mode is reduced to performing the actions revealed in Figure 3.

3. ANALYSIS OF THE COMPUTATIONAL EFFICIENCY OF THE MODEL FOR STABILIZING THE PARAMETERS OF THE HYDRAULIC CONTROL'S MAIN FRAGMENTS

The conceptual provisions of the above-described method for stabilizing the parameters of the hydraulic control of heat supply systems main fragments with throttle control were proposed and implemented in software at the information-graphic system IGS-07 [13], [15]. Computational experiments were carried out with FC and PC type models on hydraulic circuits of heat supply systems in the power systems of Sharypovo, Almaty, Kostanay, Shymkent. Summarizing the series of tests of the FC and PC models of type (1) - (5) on real hydraulic networks, the following conclusions were drawn:

- iterative processes for adjusting the hydraulic resistances of the control valves FC and PC always converge, since the conditions for the convergence of the internal iterative processes of flow distribution are always fulfilled at fixed values of the variable parameters of the hydraulic resistances in the controllers control valves. In this case, the number of external iterations for the initial data of operating conditions was in the range of 1-15 iterations.

- for emergency modes caused by an increase in consumer loads or shutdown of pumping stations the number of iterations increased to 20-40, and for individual flow and pressure controllers setpoint inconsistencies appeared, i.e. the initial setpoints of individual FCs or PCs established for the operating mode were not provided in the simulated emergency mode due to the strong influence of parametric and structural changes in the original hydraulic circuit.

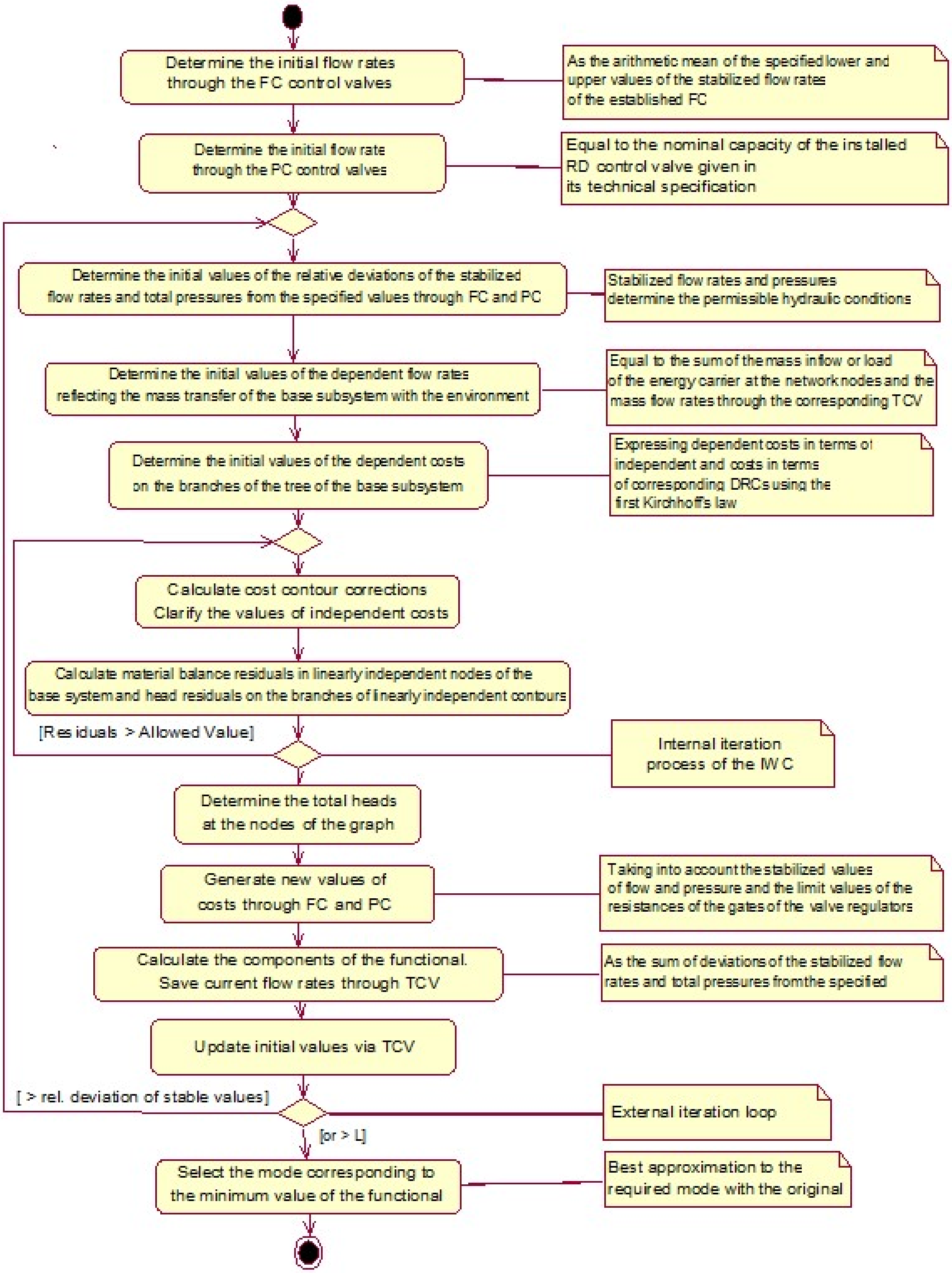

Figure 3. Algorithm for solving the stabilization problem parameters of the hydraulic control of the main HSSM fragments

The phenomenon of incompatibility of the FC and PC setpoints discovered during the study of real hydraulic circuits made it possible to unambiguously determine the requirements for the parameters and the dialogue form of the software system main modules between the database editor and the hydraulic mode processor. The database editor provides the adjustment of the FC and PC setpoints, as well as the accuracy of stabilization of the corresponding pressures and flow rates for any simulated mode, and the hydraulic mode processor provides an arbitrary setting of the number of external iterations for the FC and PC with subsequent analysis of the setpoint compatibility. The quantitative characteristics of the investigated hydraulic circuits of heat supply systems are given in the table 1.

Table 1 − Quantitative characteristics of the studied circuits

Hydraulic circuit number	Fragment of the city's power system	Hydraulic circuit graph branches						Hydraulic circuit graph nodes	Hydraulic circuit graph contours
		Pipeline sections	Consumers	Pumping stations	FC	PC	Total number of branches		
1	Sharypovo	1146	409	10	9	2	1576	1102	475
2	Almaty	1174	300	7	7	1	1489	1155	335
3	Kostanay	1393	501	20	14	2	1930	1347	584
4	Shymkent	1359	388	16	21	3	1787	1290	498
5	Nur-Sultan	1920	530	16	8	1	2475	1776	670

Studies of the computing processes efficiency were carried out for three typical modes: mode 1 - real heat loads of consumers in the current heating season and real throughput of pipeline networks; mode 2 - a 25% reduced throughput of the main highways and real heat loads of consumers in the current heating season; mode 3 - real throughput of pipeline networks and heat loads of consumers increased by 20% in relation to real heat loads in the current heating season.

During the calculation, the following characteristics were recorded:

- t_c total counting time, sec;

I - the number of iterations for the regulators FC and PC;

N - the number of regulators FC and PC with incompatible settings;

Δd - the average absolute deviation from the set points for the set of pressure regulators, meters of water column (mWC);

Δr - the average absolute deviation from the setpoints for a variety of flow controllers, tons/h (TPH).

The calculation results are shown in table 2.

Table 2 − Characteristics of the computational processes efficiency

Chain number	Mode 1				Mode 2				Mode 3			
	t_c, sec	I, iterations	Δd / Δr	N, pc	t_c, sec	I, iterations	Δd / Δr	N, pc	t_c, sec	I, iterations	Δd / Δr	N, pc
1	6	12	0.51/0.4	–	9	17	0.48/0.3	2	7	15	0.48/0.3	2
2	2	3	0.43/0.1	–	4	6	0.37/0.1	1	3	8	0.42/0.1	2
3	12	15	2.26/0.3	–	16	20	1.86/0.3	2	12	18	2.4/0.2	1
4	11	1	2.02/0.5	–	14	3	1.85/0.4	4	13	4	1.93/0.3	3
5	8	8	0.8/0.1	–	11	14	0.89/0.1	3	10	13	0.78/0.1	2

4. CONCLUSIONS

Analysis of the obtained characteristics of the computational processes efficiency obtained in the course of software implementation made it possible to formulate the following requirements and propose measures to improve the efficiency of interactive flow distribution processes in networks with flow and pressure controllers:

- in the debugged operating modes of the FCs and PCs inconsistent settings practically do not arise;

- the disturbing effect of a decrease in the throughput of the network's main sections by 25% leads to the emergence of a controllers group with incompatible settings due to the fact that a decrease in the throughput of the network leads to a significant deviation of the current flow distribution and head losses in the sections from their values in the operating mode.

- the disturbing effect of an increase in the heat loads of consumers by 20% with a constant network throughput under operating conditions leads to the emergence of a controllers group with inconsistent settings as well as in the previous case since as before because of significant deviation of the obtained flow distribution and head losses in the network sections from their values in the operating mode.

Analysis of the efficiency characteristics for computational processes obtained in the course of the practical use experience of the software implementation of the digital model made it possible to formulate the following remarks on solving the problem of stabilizing the hydraulic modes of main fragments, and to increase the efficiency of interactive processes of flow distribution in heating networks with flow and pressure controllers, to prevent the occurrence of the identified remarks:

- a disturbance with a decrease in the throughput of the main sections of the network by 25% or a disturbance with an increase in heat loads of consumers by 20% with a constant throughput of the network under operating conditions, lead to the emergence of a group of controllers with inconsistent settings due to the fact that these values of decrease throughput of the network or an increase in heat loads of consumers lead to significant deviations of the current flow distribution and head losses in the sections from their values in the operational mode;

– in the debugged operating modes of the FCs and PCs inconsistent settings practically do not arise.

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