Simulation of a Transport Standby for Ensuring Safe Heat Supply Systems Operation

S A Sazonova¹, S D Nikolenko², A A Osipov³

¹Ph.D. in Technical Sciences, Associate Professor, Department of Technosphere and Fire Safety, Voronezh State Technical University, Voronezh, Russia, e-mail: ss-vrn@mail.ru
²Ph.D. in Technical Sciences, Associate Professor, Department of Technosphere and Fire Safety, Voronezh State Technical University, Voronezh, Russia, e-mail: nikolenkoppb1@yandex.ru
³Senior Lecturer, Department of Construction Technology and Organization, Real Estate Expertise and Management, Voronezh State Technical University, Voronezh, Russia

E-mail: aosipov@vgasu.vrn.ru

Abstract. The process of development a transport (parametric) standby for cities and other settlements heat supply systems in cases of increasing pipeline diameters with constant network configuration is studied. The formation of a standby can ensure uninterrupted and safe operation of heat supply systems. Safe operation is supposed to be ensured through analysis and prevention of possible emergency situations. The development of the transport standby mathematical models is based on the energy equivalence of subscriber subsystems of heat supply systems, which distinguishes the obtained mathematical models from existing analogues. To evaluate the impact of parametric optimization results on economic indicators, a computational experiment was conducted. As an object of study, the design scheme of a residential neighborhood was considered. An analysis of the computational experiment results proved the efficiency of the obtained transport standby mathematical models for running heat supply systems. It is possible to provide transport standby for systems of any sizes and configurations or for the studied fragments of these systems. For practical use, it is of interest to calculate the parametric standby of individual houses with autonomous boiler rooms.

1. Introduction

The actions to control the flow distribution in heat supply systems (HSS) essentially represent various parametric effects on its individual elements. Transport (parametric) impacts are the most characteristic form of functioning control. This type of control is often considered operational, since it is characterized by a fairly short-term anticipation of changes in the system parameters.

In the field of HSS design usually there are three levels of tasks called hierarchical. This is the level of circuit-structural optimization, the level of circuit-parametric optimization, the level of parametric standby formation.

Scheme-structural optimization aims at the following tasks [1]:
- determination of consumer parameters on the basis of statistical data on the desired product (DP) consumption rates;
- selection of the appropriate power source location;
- monitoring network parameters to determine the relationship between consumers and power sources.

When solving these problems, it is necessary to take into account the requirements for reliability and efficiency. The methodology for solving the structural reservation problem for HSS is considered in [2].

Parametric optimization includes the following tasks:
- determine the pipe diameters in the system;
- analyze the calculated traffic distribution for different types of consumption.

These tasks are solved by using a given scheme and information about the main relationships for HSS. In the paper [3] V.G. Shukhov proposed a classical solution for this level of optimization.

In Russia, in the construction of central heating systems, an analytical approach to solve the problem of optimizing parameters has appeared. It is studied, for instance, in A.M. Zanfilova’s papers [4]. The analytical method has been thoroughly studied by N.N. Abramova and V.Ya. Khasileva [5, 6]. An interesting approach is described in [7, 8].

In [9, 10, 11], based on the use of energy equivalence, the problem of formalized coordination between the developed steady flow distribution model and the problem of optimizing the parameters of water supply systems have been solved. In [12, 13], mathematical models of flow distribution for HSS have been developed.

The dynamic programming method (DPM) and its modifications have been actively developed as alternative approaches [14, 15, 16, 17]. The DPM is very effective for optimizing the parameters of the branching system [18, 19, 20, 21, 22], but it requires the use of the algorithm for "docking" [23] the pressure in the branching units.

The parametric standby development requires reliability of the designed system (with a known configuration and composition) ensured by a parametric standby. In practice, it all comes down to calibration hydraulic calculations. The consumption limits are fixed [5].

2. Simulated hydraulic calculations

Among the considered methods for solving the problem of running HSS control, the most effective one has proved to be the energy equivalence method described in [9, 11]. At the same time, it is important to use simulation modeling to calculate the transport standby and assess the HSS reliability. It consists of simulated hydraulic calculations, including analysis of the flow distribution in the system in case of its various elements failure [12].

The calculation task is to determine the total carrier consumption through all sources for the studied system elements. Ultimately, it is necessary to determine the deviation from the initial unperturbed state of the system. In general, the loss of equipment power in an emergency can be considered as a certain (hydraulic) part of the reliability model [24]. In [25, 26], problems of heat supply systems optimizing and finding the optimal solution for the reconstruction of HSS have been considered.

In general, the task of summarizing the results of HSS failure simulation based on the energy equivalence has not yet been solved. There are only its analogues for gas and water supply systems [9, 10].

The results of computational experiment were analyzed in [10]. On the basis of this, a clear relationship was established between the relative flow rate at the site \( \bar{Q}_i = Q_i / \bar{Q}_2 \) through the system power supplies \( \bar{Q}_2 \) and the relative loss of production capacity in case of accident. The ratio \( \Delta \bar{Q} = (\bar{Q}_2 - \bar{Q}_2^w) / \bar{Q}_2 \) was obtained. In this formulation the index \((\Xi)\) denotes a total desired product (DP) consumption in the network, and the index “ac” indicates an accident condition [27].

After processing by the least squares method (LSM) with two variable parameters, the dependence was obtained

\[
\Delta \bar{Q} = a\bar{Q}_i^2 + b\bar{Q}_i.
\]
For further application of the HSS standby method, let us assume that the coefficients $a$ and $b$ in the equation (1) are known.

3. Simulating the transport standby of heat supply systems

Let us consider the process of forming a parametric standby for HSS. As the initial information for the backup, we use reduced (limited) DP consumption $g_{lj}^{lim}$. The value $g_{lj}^{lim}$ can be considered a function of time.

Assume that in the estimated area (EA) of the entire set of power units (PU), only consumer connections PU are controlled in case of limited consumption $\{j \in \mathcal{J}_{\eta(p)} \cup \mathcal{J}_{\eta(g)} \cup \mathcal{J}_{\eta(f)}\}$.

The failure state of the system is determined by the following conditions: if the $i$-th partial failure in the PU occurs within the EA, then the selection changes and the condition $g_{ac}^{\alpha} \leq g_{lj}^{lim} - K_{lj}^{lim} \times \hat{g}_{lj}$ is satisfied, (where $\hat{g}_{lj}$ is the estimated medium consumption from the PU $j$).

For a steady flow distribution, total consumption $g_{e} = \sum_{j} g_{lj}$; \{$j \in \mathcal{J}_{\eta(p)} \cup \mathcal{J}_{\eta(g)} \cup \mathcal{J}_{\eta(f)}\}$ corresponds to the HSS production capacity. If all the conditions $g_{lj}^{ac} \geq K_{lj}^{lim} \times \hat{g}_{lj}$ for the selected PU are met provided that the diameter is increased, it is assumed that such a system will recover after the accident.

Taking into account the energy equivalence principles [9, 11], we find that the selection $\hat{g}_{lj}$ for the subsystems of hot water supply and heating, as well as the pressure $\hat{h}_{lj}$ in the PU $j$, are interconnected through the full hydraulic resistance of the corresponding equivalent sections $\xi_{lj}^{\alpha}$. They are also connected using the relation for the objective function in LSM and the Bernoulli equation in the static estimation problem for HSS [28, 29]. The failure of the $i$-th element should be considered as a disturbed state of the system.

The value $\xi_{lj}^{\alpha}$ can be determined in accordance with the HSS nominal operating mode.

The position in accordance with the known consumption standards

\[
\begin{align*}
    h_{lj}^{lim} - h_{open} &= \xi_{lj}^{\alpha} \left( g_{lj}^{lim} \right)^{a} \\
    h_{lj}^{lim} - h_{closed} &= \xi_{lj}^{\alpha} \left( g_{lj}^{lim} \right)^{a}
\end{align*}
\]

(2) can be set at a minimum potential level in the PU $h_{lj}^{lim}$, below which the hydraulic resistance does not allow to pass the limited selection to the consumer. Relation (2) is used for hot water supply subsystems (with an open circuit), and (3) with a closed circuit for hot water supply and heating subsystems.

Therefore, the search for standby should be based on two conditions:

\[
\begin{align*}
    g_{lj}^{ac} &\geq g_{lj}^{lim} \\
    h_{lj}^{ac} &\geq h_{lj}^{lim}
\end{align*}
\]

(4)

The first standby creation stage is the analysis of the perturbed state, based on the flow distribution model [12]. The second stage can be a discrete nonlinear mathematical programming problem [30]. Instead of nominal consumption $\hat{g}_{lj}$, limited selections $\hat{g}_{lj}^{lim}$ are established, determined from the expression:

\[
\hat{g}_{lj}^{lim} = K_{lj}^{lim} \times \hat{g}_{lj}
\]

(5)

In accordance with the approximation algorithm, the diameter correction for each iteration step is performed by solving a system of linear equations in matrix form:

\[
\begin{align*}
    A_{mn}^{x} G_{n}^{m} x^{x} \delta D_{nl} &= 0_{mn}^{x} \\
    K_{ro}^{x} B_{m}^{ro} x^{x} \delta D_{nl} &= 0_{ro}^{x} \\
    C_{pro}^{x} B_{m}^{pro} \delta D_{nl} &= M^{t} p_{x} x^{x} \delta \hat{H}_{nl}^{x}
\end{align*}
\]

(6)
where \( \hat{\delta D}, \hat{\delta H} \) are the column matrices that adjust the diameter and potential in the corresponding PU; the ratios 
\[ G_i = (1 + \delta)Q_i^{-\alpha}D_i^\beta, \quad B_i = s_i \delta D_i^{(1+\delta)}Q_i^\alpha L_i \]
are introduced; the marks in accordance with [12] are also used.

During the sequential solution of equations (6) - (8), increasing the diameters of the reserved sections, we reproduce the pressure values in the PU in the case of accidents.

Meanwhile, since the economic model (6) imposes restrictions on the standby process, which, when switching from an accident state to a healthy state of the system, allows us to determine the extreme costs and identify the optimal standby option.

4. Results of the computational experiment
In order to assess the impact of the parametric optimization procedure on the economic indicators, the parameters of the HSS were experimentally determined on the example of a residential neighborhood, the calculated scheme of which is shown in figure 1. In figure 1, PU are highlighted in red. The results of the computational experiment for HSS generally correspond to the results considered in [9] for gas supply systems and are presented in figure 2. Thus, the correctness of the developed models of the transport reserve for HSS was proved.

![Figure 1. The HSS design model.](image1.png)

![Figure 2. The influence of parametric optimization on the HSS economic indicators according to the computational experiment results.](image2.png)

On the horizontal axis in Figure 2, the value \( \hat{m} \) expressed as a percentage of the power units total number in the HSS with known potentials in relation to the number of power units not subjected to optimization was laid off. When \( \hat{m} = 100\% \), the regulators characteristics or the current values of the potentials were determined in the power units. At \( \hat{m} > 100\% \), potentials were determined in the power units, and at \( \hat{m} < 100\% \), selection was determined instead of pressure.

The vertical axis in Figure 2 expresses the HSS metal content at the design level.

The most economical, as expected, is the option when \( \hat{m} = 100\% \). For all other five conducted computational experiments, it was revealed that economic indicators sharply deteriorated.
As a result, it can be noted that carrying out parametric optimization in the sections according to the differential pressure parameters makes it possible to protect the HSS from an excessive increase in the sections diameters. As a result, it is possible to perform parametric optimization with the required flow distribution parameters in order to identify the minimum costs.

5. Conclusion
For the initial heat supply system under study, without the standby created, the sequential sections diameters selection based on the HSS perturbed state analysis can be considered as the process of standby determining. At the same time, the use of subscriber subsystem equivalents makes it possible to solve the problem within the unary design scheme. In this case, the boundary conditions with limited consumption are associated with the required limitations on the HSS operation mode.

The obtained numerical experiment results proved the efficiency of the developed transport standby models for running HSS. In practice, the proposed approaches to the transport standby implementation task for larger or small heat supply systems can be used. They can be used, for example, to calculate the transport standby of large cities. The proposed approach can be also used to calculate changes in the transport standby of a separate house with an autonomous boiler room.

The studied issues significantly express the content of the improving the analytical method of analysis in the problem of optimizing the heat supply systems parameters, taking into account various restrictions.

References
[1] Evdokimov A G, Tevyashev A D and Dubrovsky V V 1990 Modeling and optimization of flow distribution in engineering networks (Moscow) 368 p
[2] Sazonova S A 2010 Structural reservation of heat supply systems Bulletin of Voronezh State Technical University vol 6 12 pp 179–183
[3] Shukhov V G 1895 Pipelines and their application to the oil industry (Moscow) 38 p
[4] Zanfirov A M 1933 Feasibility study of water heating networks Heat and power no 11 pp 4–10
[5] Abramov N N 1984 Reliability of water supply systems (Moscow) 216 p
[6] Khasilev V Ya, Merenkov A P, Kaganovich B M, Svetlov K S and Takaishvili M K 1978 Methods and algorithms for heat networks calculating (Moscow) 175 p
[7] Kaganovich B M, Voropay N I, Stennikov V A and Novitsky N N 2017 The development of models and methods of circuit theory and their energy applications Bulletin of the Russian Academy of Sciences Energy 6 pp 24–32
[8] Ilkevich N I, Dzyubina T V and Surnin N V 2016 Determination of rational methods of gas supply systems standby taking into account multilevel modeling of their development Bulletin of the Russian Academy of Sciences Energy 1 pp 58–69
[9] Kvasov I S 1998 Analysis and parametric synthesis of pipeline hydraulic systems based on functional equivalence (Voronezh) 30 p
[10] Panov M Ya, Kvasov I S, Shcherbakov V I and Scherbakov K V 1997 On the issue of modeling the unloaded standby in the designed hydraulic systems News of higher educational institutions Building 11 p 91
[11] Kvasov I S, Panov M Ya, Shcherbakov V I and Sazonova S A 2001 Energy equivalence of large hydraulic systems for the life support of cities News of higher educational institutions Building 4(508) pp 85–90
[12] Sazonova S A 2011 The results of the development of mathematical models for analysis of flow distribution for heat supply systems Bulletin of the Voronezh State Technical University vol 7 5 pp 68–71
[13] Sazonova S A 2010 Models for assessing the disturbed state of a heat supply system Engineering Physics 3 pp 45–46
[14] Headley J 1967 Nonlinear and dynamic programming (Moscow) 506 p
[15] Sukharev M G and Stavrovsky E R 1975 Optimization of gas transport systems (Moscow) 278 p
[16] Sukharev M, Kosova K and Popov R 2018 Mathematical and computer models for identification and optimal control of large-scale gas supply systems Energy pp 1–8
[17] Sukharev M and Kulik V 2017 The impact of information uncertainty on the problems of medium- and long-term planning of the operation gas transport systems modes Energy pp 1–8
[18] Sukharev M and Kosova K 2017 New diagnostic methods aimed at increasing of reliability and safety of the main pipeline transport In the collection E3S Web of Conferences p 02001
[19] Merenkov A, Senna E, Sumarokov S and others 1992 Mathematical modeling and optimization of heat, water, gas supply systems (Novosibirsk) 406 p
[20] Lutsenko A and Novitsky N 2018 The modified dynamic programming method for optimizing the hydraulic modes of distribution heat networks Computational technologies vol 23 6 pp 47–63
[21] Novitsky N and Lutsenko A 2016 Discrete-continuous optimization of heat network operating conditions in parallel operation of similar pumps at pumping stations Journal of Global Optimization vol 66 1 pp 83–94
[22] Novitsky N, Alekseev A, Grebnev O, Lutsenko A, Tokarev V and Shalaginova Z 2018 Multilevel modeling and optimization of large-scale pipeline systems operation Energy pp 1–14
[23] Merenkov A and Khasilev V 1985 Theory of hydraulic circuits (Moscow) 278 p
[24] Sennova E, Smirnov A, Ionin A and others 2000 Reliability of energy systems and their equipment Reference edition (Novosibirsk) vol 4 351 p
[25] Stennikov V, Oshchepkova T and Stennikov N 2013 Optimal expansion and reconstruction of heat supply systems: methodology and practice International Journal of Energy Optimization and Engineering vol 6 4 pp 59–79
[26] Barakhtenko E, Oshchepkova T, Sokolov D and Stennikov V 2013 New results in development of methods for optimization of heat supply system parameters and their software implementation International Journal of Energy Optimization and Engineering vol 4 4 pp 80–99
[27] Kvasov I, Panov M and Sazonova S 1999 Diagnostics of leaks in pipeline systems during loose gauge surveys News of higher educational institutions Building 9(489) pp 66–70
[28] Kolodyazhny S, Sushko E, Sazonova S and Sedaa A 2013 The solution of the problem of gas supply systems static assessment Scientific Bulletin of Voronezh State University of Architecture and Civil Engineering Construction and architecture 4(32) pp 25–33
[29] Kvasov I, Panov M and Sazonova S 2000 Statistical assessment of the pipeline systems state based on functional equivalents Bulletin of higher educational institutions Building 4(496) pp 100–105
[30] Kafarov V and Meshalkin V 1991 Design and calculation of optimal process piping systems (Moscow) 368 p