Investigation of monitoring tasks of the dynamics of heating networks temperature states

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Abstract. In order to monitor heat supply systems for the purpose of uninterrupted heat supply to consumers, it is necessary to create full-scale monitoring systems that would improve the quality of decisions on controlling the development and functioning of systems based on the information coming from continuously operating measuring systems. The main result and purpose of monitoring in this case will be the assessment of the current regime and its compliance with the established requirements. The article investigates the task of monitoring the dynamics of temperature states of heating networks. As the closing equation in the thermal-hydraulic model, it is proposed to use the equation based on the energy conservation law, describing physical processes related to heat transfer through the walls of pipelines and heat transfer into the environment.
Keywords: heating networks, heat supply, temperature states monitoring, modeling, thermal-hydraulic model.

1 Introduction

At present, Russia is undergoing full-scale processes of digitalization of the economy and its industries, including the energy sector, an integral part of which are heat supply systems [1]. One of the components of such processes is the creation of full-scale monitoring systems, which would improve the quality of decisions on controlling the development and functioning of systems on the basis of information coming from continuously operating measurement systems. Synthesis of these components opens up new possibilities for effective coordination of interests, requirements and possibilities of all parties involved in the processes of production, transport and consumption of the target product.

In the article state monitoring will be understood as a process of continuous observation of production, distribution and consumption of heat energy on the basis of the initial information coming with a given periodicity from the same automated information and measurement system. As a methodological basis for the tools and algorithms of the initial information processing, based on the purpose of the monitoring object, it is proposed to use methods of the theory of hydraulic circuits, planning of experiments, statistical evaluation, parametric identification (state estimation) [1,2]. The main result and purpose of monitoring

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must be the assessment of the current state and its compliance with the requirements (constraints). Violation or non-compliance of the state parameters with such requirements will be the basis for formation of control impacts.

Thus, one of the main objectives of monitoring is to provide information and analytical support for informed control decisions to ensure the reliability, quality and efficiency of heat supply processes.

A large number of works both in Russia [3-15] and abroad [16-18] is devoted to the identification of pipeline systems (PLS) of various types and purposes, which indicates their relevance, complexity and multidimensionality. A significant limitation of most of the proposed approaches is the stationary formulation of the problems.

Recently, due to the new trends of transition to intelligent PLS, it is necessary to consider the processes of their control in real time. This, in turn, requires consideration of state estimation tasks (parametric identification) as tasks of passive identification based on the results of dynamic (obtained during the operation of the system and constantly changing in time) measurement data.

The subject of the article is the analysis of the accumulated experience in modeling of the dynamic temperature states of PLS of different types and purposes for the possibility of its subsequent use in solving inverse problems.

2 Heating network monitoring states and their features

When modeling states of PLS operation there are different models of hydraulic, temperature and thermal-hydraulic states of PLS.

When modeling the steady-state hydraulic state, the model includes the equation of the first (material balance in nodes) and the second Kirchhoff laws, as well as the equation reflecting the laws of pressure drop when the heat carrier flows through the branches. The steady-state temperature model includes the heat balance equation in the nodes, the condition for complete mixing of flows in the nodes and the equation reflecting the laws of temperature drop when the heat carrier flows through the branches.

Traditionally for modeling of nonstationary states of fluid flow the system of partial derivative equations is used, including modification of equation of motion and modified equation of continuity of flow. This model describes the phenomenon of hydraulic shock, which occurs when there are violations of the normal state of PLS operation, has a short-term nature and is not characteristic for the states of PLS operation. Application of this model to describe non-stationary states of PLS of real dimension increases the complexity and complexity of calculations. Therefore, it is not reasonable to use this model to describe gradually changing in time (quasi-stationary) states.

In many works, when modeling nonstationary states of PLS functioning, the authors make attempts to reduce these states to a set of continuously following one another stationary states, in which the parameters characterizing the system do not change during the observation time. This approach is easily applicable in modeling hydraulic states.

Temperature states are difficult to reduce to a set of stationary ones, since temperature states are almost always transient, due to fluctuations in the ambient temperature and the lag of the temperature front. And this is one of the features of the problem, which will be given special attention below.

3 Mathematical model of the temperature state

Usually as an initial mathematical model when considering the steady-state temperature state, mode $U_H(Z_H)$ (1) is used, which is a subsystem of the thermal-hydraulic state model [19]

$$U_H(Z_H) = \begin{pmatrix} \bar{A}_1 X t_b - \bar{A}_2 X t_e - \theta \\ \chi_b(t_b - \bar{A}_1^{\mathrm{T}} T) - \chi_e(t_e - \bar{A}_2^{\mathrm{T}} T) \\ t_e - \Phi(x, t_b, \alpha_2) \end{pmatrix}, \tag{1}$$

where $U_H(Z_H) = 0$ – model of the temperature state with the parameter vector $Z_H = \{x, \bar{Q}, t_b, t_e, T_{in}, T, \alpha_2\}$; $\bar{A}$ – $(m \times n)$- incident matrix of nodes and branches of the design scheme; $m = m_1 + m_2$ – number of scheme nodes, where m_1 – the number of nodes with outflow and simple connection nodes, and m_2 – number of nodes with inflow; n – branch number; $\bar{A}_1$ – branch orientation matrix obtained from the matrix $\bar{A}$ by replacing the elements equal to –1 by 0; $\bar{A}_2$ – branch orientation matrix obtained from the matrix $\bar{A}$ by replacing the elements equal to 1, by 0; x – flow rates vector on n branches; $\bar{Q}$ и $\bar{P}$ – vectors of nodal flow rates and pressures in m nodes; t_b, t_e – the temperature vectors, respectively, at the beginning and at the end of the branches; X – $(n \times n)$ - diagonal matrix with components $c_i x_i$ on the main diagonal; θ – m-dimensional vector of nodal heat flow rates with elements $\theta_j = c_{in} Q_j T_{in,j}$ in the case of an inflow, $\theta_j = c_j Q_j T_j$ – in the case of an outflow, $T_{\text{in},j}$ – inflow temperature, T_j – mixing temperature of the flows in the node j; $\bar{T}$ – vector of mixed flow temperatures in the nodes; $\chi_b = \mathrm{diag}\{\vec{\chi}_1, ..., \vec{\chi}_n\}$ and $\chi_e = \mathrm{diag}\{\vec{\chi}_1, ..., \vec{\chi}_n\}$ – diagonal matrices with elements $\vec{\chi}_{b,i} = [1 + \mathrm{sign}(x_i)]/2$, $\vec{\chi}_{e,i} = [1 - \mathrm{sign}(x_i)]/2$, which have the following properties: $\vec{\chi}_{b,i} = 1$, if x_i >0, and $\vec{\chi}_{\text{н},i} = 0$, if x_i <0; $\vec{\chi}_{e,i} = 1$, if x_i <0, and $\vec{\chi}_{e,i} = 0$, if x_i >0; $\Phi(x, P, t_{\text{н}}, \alpha_2)$ – vector-function of branch thermophysical characteristics; c – mass heat capacity of water.

However, when considering the dynamic temperature states of heating networks (HN), the model (1) presented above cannot be used due to the fact that fluctuations in the external environment parameters and the lag of the temperature front lead to imbalance in its equations.

The main problem in modeling of dynamic states is to find a specific dependence for the temperature drop along the length of the pipeline.

4 Formulation of tasks for HN temperature states monitoring based on the involvement of dynamic state models

For simplicity, we will assume that the coefficients characterizing the technical condition (coefficients of hydraulic resistance, heat transfer, etc.) are known. Formalization of this problem in general reduces to the following [20].

Discrete analogues of the equations of nonstationary flux distribution can be represented as two basic subsystems of equations::

1) *dynamics model* $X_R^{\tau} = \omega(X_R^0)$, where X_R^{τ} – a vector of independent state parameters at the current state of time; X_R^0 – vector of independent state parameters at the initial moment of time;

2) *measurement model* $\tilde{Z}_1^{\tau} = \psi(X_R^{\tau}) + \xi_{Z1}^{\tau}$, where $\tilde{Z}_1^{\tau}$ – measurement vector; ξ_{Z1}^{τ} – measurement error vector.

Thus, the task of temperature monitoring can in principle be reduced to the solution of the problem on the unconditional minimum of the function $\Phi(X_R^{\tau}) = \frac{1}{2}\left[\tilde{Z}_1 - \psi(X_R^{\tau})\right]^{\mathrm{T}} C_{Z_1}^{-1}\left[\tilde{Z}_1 - \psi(X_R^{\tau})\right]$, where C_{Z_1} – covariance matrix of measurement errors.

The main problem in modeling of the dynamic temperature states is to find a specific dependence linking the temperatures at the ends of the pipeline with the change in temperature along the length of the pipeline [23]. This dependence should be based on the energy conservation equation:

$$\lambda F \frac{\partial}{\partial l}\left(\frac{\partial t(l,\tau)}{\partial l}\right) - 2\pi R k\left(t(l,\tau) - t_{env}(\tau)\right) = c\rho F \frac{\partial t(l,\tau)}{\partial \tau} + cG\frac{\partial t(l,\tau)}{\partial l},$$

where τ – time coordinate ($\tau = \overline{0,\Omega}$); l – coordinate along the length of the pipeline L, ($l = \overline{0,L}$); λ – heat transfer coefficient; F – площадь поперечного сечения потока теплоносителя; $t(l,\tau)$ – the temperature of the coolant at the time τ and at the point l along the length of the pipeline; R – outer radius of the pipeline; k – heat transfer coefficient from the heat carrier (through the pipe wall) to the environment; t_{env} – environmental temperature; c – heat capacity of the heat carrier; ρ – heat carrier density; G – mass flow rate.

This equation includes four components, which characterize: 1) the amount of heat received by the heat carrier due to its thermal conductivity; 2) the amount of heat that is released from the heat carrier into the environment; 3) the change in the internal energy of the heat carrier; 4) the energy required by the heat carrier to move along the length of the pipeline (mechanical work). However, the use of this differential equation directly in the task of HN monitoring is associated with significant difficulties, as it is not directly related to the nodal (including measured) temperatures. As a result of literature analysis in the field of modeling of dynamic processes of heat and mass transfer in cylindrical pipelines [21], possibility of application of transformations [22-24] was established, which allow to obtain analytical solution of energy conservation equation to determine the heat carrier temperature at any point along the length of the pipeline at any time, and which can potentially be used as a basis for dynamic model of temperature state of the HS with its monitoring –

$$t(l,\tau) = e^{-\frac{2k}{c\rho R}\tau} \cdot \left[t_0\left(x - \int_0^{\tau} v(\tau)d\tau\right) + \frac{2k}{c\rho R}\int_0^{\tau} e^{\frac{2k}{c\rho R}\tau} t_{env}(\tau)d\tau \right] \text{ with } l - \int_0^{\tau} v(\tau)d\tau \ge 0.$$

5 Conclusion

In this work, a study of the task of monitoring the dynamics of HN temperature state has been carried out.

he equation based on the energy conservation equation describing physical processes related to heat transfer through the walls of pipelines and heat release into the environment is proposed to be used as a closing relation in the thermal-hydraulic model.

n the future, it is planned to develop the finite state methods and algorithms for solving the set task on the basis of state estimation methods (sequential identification of temperature states) of hydraulic circuit theory [25].

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References

1. N.N. Novitsky, Z.I. Shalaginova, A.V. Alekseev, et al., Proceedings of the IEEE, **109 (9)**, 1596 (2020)
2. Decree of the Government of the Russian Federation #808 of 08.08.2012 (ed. from 14.02.2020)
3. Oksana Grebneva, and Nikolay Novitsky, Proc. of the XVII Meet. Conf. Mathematical models and methods of the analysis and optimal synthesis of the developing pipeline and hydraulic systems, **219**, 28 (2020)
4. E.N. Zhukovsky, *On Hydraulic Shock in Water Pipes* (Ed. Tekhn.-Theoretichesk. Lit., Leningrad, 1949) [in Russian]
5. I.A. Charny, *Unsteady motion of real liquid in pipes* (State Publishing House of Technical Theoretical Literature, Moscow, 1951) [in Russian]
6. B.N. Gromov, B.I. Svinukhov, Electric Stations, **10**, 18 (1972) [in Russian]
7. B.N. Gromov, L.P. Kanina, K. Nestke, P. Schneidenbach, Thermal Power Engineering, **7**, 36 (1981) [in Russian]
8. B.N. Gromov, L.P. Kanina, V.G. Sidler, New Information Technologies of Management of Development and Functioning of Pipeline Power Systems, 69 (1993) [in Russian]
9. N.N. Novitsky, E.V. Sennova, M.G. Sukharev, V.K. Averyanov, et al. Hydraulic Chains (ESI SB RAS, Irkutsk, 2000) [in Russian]
10. M. Chertkov, N.N. Novitsky, Energy, **184**, 22 (2019)
11. N.N. Novitsky, *Estimation of parameters of hydraulic circuits* (Nauka, Novosibirsk, 1998) [in Russian]
12. Nikolay N. Novitsky and Oksana A. Grebneva, Proc. of the XVI Meet. Conf. Mathematical models and methods of the analysis and optimal synthesis of the developing pipeline and hydraulic systems, **39**, 03004 (2018)
13. O.A. Grebneva, N.N. Novitskii, Thermal Engineering, **61 (9)**, 685 (2014)
14. O.A. Grebneva, N.N. Novitskii, Thermal Engineering, 61 (10), 754 (2014)
15. V.V. Tarasevich, Izvestiya vyssheykh obrazovatel'nykh uchebnykh obrazovatel'nykh. Construction, **7 (691)**, 92 (2016) [in Russian]
16. Ronghe Wang, Zhixun Wang, Thomas M. Walski, Mal Sharkey, Samuel R. Coran and Sheldon H. Zemell, Proc. 11th Int. Conf. on Computing and Contgrol for Water Industry, 877 (2011)
17. Irina Gabrielaitiene, Benny Bohm, Bengt Sunden. Energy Conversion and Management, **48**, 78 (2007)
18. Jinfu Zheng, Zhigang Zhou, Jianing Zhao, Jinda Wang, Applied Thermal Engineering, **123**, 682 (2017)

19. N.N. Novitskii, O.A. Grebneva, V.V. Tokarev, Thermal Engineering, **65 (7)**, 453 (2018)
20. N.N. Novitsky Izvestiya Rossii Akademii Nauk. Power Engineering, **6**, 87 (2000) [in Russian]
21. P.A. Bogoslovsky, *Ice regime of pipelines of hydroelectric power plants* (Gosenergoizdat, Moscow, 1950) [in Russian]
22. B.N. Devyatov, N.D. Demidenko, *Theory and Methods of Analysis of Controlled Distributed Processes* (Nauka, Novosibirsk, 1983) [in Russian]
23. A.G. Butkovsky, *Theory of Optimal Control of Systems with Distributed Parameters* (Nauka, Moscow, 1965) [in Russian]
24. V.I. Panferov, Technical problems of heat and gas supply, ventilation, water supply and water disposal systems, 96 (2002) [in Russian]
25. A.P. Merenkov, V.Ya. Khasilev, Theory of hydraulic circuits (Nauka, Novosibirsk, 1985) [in Russian]