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DISTRICT HEATING COGENERATION AND HEAT NETWORKS

Analysis of Additional Factors in Determining the Failure Rate of Heat Network Pipelines

I. G. Akhmetova[a], * and T. R. Akhmetov[b]

[a] *Kazan State Power Engineering University, Kazan, 420066 Russia*
[b] *AO Kazenergo, Kazan, 420021 Russia*
**e-mail: irina_akhmetova@mail.ru*

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Abstract—For estimating the reliability of existing and newly developed circuit diagrams of heat networks, a special procedure is applied. By applying this procedure, which uses such input data as the length and operation time of pipeline segments, it is possible to determine the availability factors and probabilities of failure-free operation for a heat network. The aims of this study are to reveal and consider additional factors in determining the failure rate of heat network pipelines and to develop a new procedure for calculating indicators characterizing the reliability of heat supply to consumers. The failure rate of heat network elements depends, apart from the time they have been in operation, on the pipeline wall residual thickness, corrosion activity of soil, pipeline material, failure of a pipeline batch, other (previous) bursts in the considered segment, conduit flooding (flooding traces), and intersections with other utility lines. Additional factors significantly influencing the heat supply reliability, which, however, have not been included in the currently used procedure, are revealed, and an algorithm for calculating the heat network reliability is developed. The influence of the additional factors on the reliability of heat network operation is evaluated proceeding from the field data presented by regional heat supply companies. The influence of additional factors is taken into account in elaborating the new procedure and algorithm for calculating the heat supply's reliability indicators. The results from numerical and experimental investigations confirmed the possibility of using the obtained functional dependencies for elaborating a procedure of calculating heat network's reliability taking external factors into account.

Keywords: heat supply, heat networks, reliability, failure rate, soil corrosiveness, conduit flooding, pipeline wall residual thickness, additional factors' accounting coefficient

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According to the Russian Federation's Federal Law "About Heat Supply" [1], the main principle of the state policy in the field of heat supply is "assurance of heat supply reliability in accordance with the relevant technical regulations." The regulatory and legislative acts developed within the framework of fulfilling the law's requirements rest on the heat supply's reliability assessment procedures [2–4]. The shortcoming of the procedure set out in [2] is that it does not yield a quantitative reliability indicator value. The reliability indicator established in [3] is defined as the number of heat supply interruptions connected with abnormalities in the operation of heat supply sources and heat networks. This indicator is rather subjective in nature and may vary over a wide range for several years.

To determine the reliability of heat supply circuit diagrams in designing them, the procedure outlined in [4] is applied, which uses the failure rate and mean time to restore the serviceability of heat supply mains and equipment as input data. The actual reliability level of a considered heat supply system must be estimated by processing statistical data on the failures of its components. In accordance with [5], to make sure that statistical samples had the necessary uniformity, completeness, and significance, the collection of input data in line with the form recommended in [6] should be set up in each system.

If statistical data are not used, the heat supply mains' failure rate λ is calculated, taking the mains' operation time into account using the Weibull distribution equation [7] with the initial failure rate of 1 km of a single-line heat supply main's λ_{in}, which is equal to 5.7×10^{-6} 1/(km h) or 0.05 1/(km year) [8] and corresponds to the normal operation time of a new heat supply main after its breaking-in period. The mean failure rate of shutoff and control valves (e.g., a gate valve) is taken as equal to 2.28×10^{-7} 1/h or 0.002 1/year [8].

For the heat supply schemes of cities and municipal districts with a total number of inhabitants of more than 100000 people, the reliability indicators are calculated for nodes with generalized consumers. In this case, the coefficient corresponding to the representative building categories or buildings with the worst thermal stability in the considered node is taken as the building's heat storage coefficient.

By using the developed procedure [4, 9], it is possible to calculate the availability factors and probabilities of heat network failure-free operation proceeding from information on the length and operation time of pipeline segments in a system. However, this procedure does not take into account some factors that directly affect the reliability of a heat network's operation.

In [10–12], a procedure for comprehensively analyzing the reliability of heat supply to consumers and for determining the heat supply system's optimal reliability parameters is presented. It is pointed out that the external factors influencing the heat supply's reliability depend on a multitude of conditions that are not connected with the parameters of system components, structure, and properties [10]. By using the mathematical model developed by the authors, it is possible carry out the design analysis of a heat supply system taking into account the effect of internal and external factors. In so doing, the climatic conditions (drop of outdoor air temperature below its design value) are taken as external factors.

It should be pointed out that the heat supply's reliability depends on a broader list of external conditions. The practical significance of reliability indicators consists not only in estimating the reliability of the existing heat supply system but also in developing a tool for long-term scheduling of programs for carrying out overhaul, refurbishment, and modernization of the heat supply system's components. The need for analyzing the reliability of particularly heat networks is corroborated by the complexity of determining—both visually and with the use of instruments—the condition of underground pipelines. An analysis that is based only on information about pipeline failures and lifecycles does not allow the long-term reliability scheduling problem to be solved to a full extent.

The aims of this study are to reveal and take into account additional factors in determining the failure rate of heat network pipelines and to develop a new procedure for calculating indicators characterizing the reliability of heat supply to consumers. This aim is reached by solving the following tasks:

(1) determining the additional factors having an essential effect on the reliability of heat supply to consumers, which, however, have not been included in the approved procedure and algorithm for calculating the reliability of heat networks;

(2) estimating the effect of additional factors on the reliability of heat network operation based on the field data obtained from regional heat supply companies;

(3) taking into account the influence of additional factors in elaborating a new procedure and algorithm for calculating the indicators characterizing the reliability of heat supply to consumers; and

(4) developing a computer program for calculating the indicators characterizing the reliability of heat supply to consumers using the new calculation procedure and algorithm.

DETERMINATION OF ADDITIONAL FACTORS INFLUENCING THE FAILURE RATE OF HEAT NETWORK COMPONENTS

Application of the procedure set out in [4] makes it possible to calculate the heat network's availability factors and probabilities of its failure-free operation proceeding from information on the lengths and operation times of system pipeline segments. However, this procedure does not take into account some factors directly affecting the reliability of the heat network's operation.

In this article, we assumed that the following factors (parameters) influence the failure rate of heat network components apart from their operation time: the pipeline wall residual thickness (K_1), other (previous) bursts in a segment (K_2), soil corrosiveness (K_3), conduit flooding (flooding traces) (K_4), and intersections with utility lines (K_5). The influence of these factors on the reliability of the heat supply to consumers was estimated in [13].

For solving the question about including some or other factors in the new procedure and algorithm for calculating the reliability indicators of heat supply to consumers, we analyzed the entire amount of statistical data accumulated by heat supply companies about the bursts that occurred in different segments of the heat network in the city of Kazan [14]. Heat network failures caused by external mechanical impacts (bursts caused by collision with motor vehicles, and breaks of conduit cover plates) were excluded from the analysis, because such factors cannot be predicted statistically.

The information about bursts was grouped subject to the availability of some or other factors (totality of factors). The material of which the pipelines are made was not taken into account, because information about the bursts of steel pipelines has by now been accumulated. Modern structural materials began to be used in constructing heat networks relatively not long ago; therefore, statistical information about bursts in segments containing polymeric pipelines is not available.

During the analysis of data, a correlation between the pipeline segment operation time τ and the number of its failed pipeline batches n (an additional parameter) was established:

τ, years	n, %
More than 29	85
28	85
24	75
19	75
17	60
16	50
14	50
8	10
6	5

Since the segment operation time is the main parameter in calculating the failure rate of heat network components, we had to do away with this additional parameter. The number of factors affecting the heat network reliability is limited to the actual data on damages at heat supply companies.

ASSESSING THE INFLUENCE OF ADDITIONAL FACTORS ON THE FAILURE RATE OF HEAT NETWORK COMPONENTS

According to the procedure presented in [4, 9], the failure rate of heat network components, 1/(km h), is calculated from the formula

$$\lambda = \lambda_{in}\left(0.1\tau\right)^{\alpha-1}, \qquad (1)$$

where α is the coefficient that takes into account the pipeline segment operation time,

$$\alpha = \begin{pmatrix} 0.8 \text{ with } 0 < \tau \le 3; \\ 1.0 \text{ with } 3 < \tau \le 17; \\ 0.5e^{\left(\frac{\tau}{20}\right)} \text{ with } \tau > 17. \end{pmatrix} \qquad (2)$$

For taking into account the factors recommended in [8], the existing procedure was supplemented with the coefficient considering the additional parameters

$$K_i = f(K_1, K_2, K_3, K_4, K_5). \qquad (3)$$

The failure rate of heat network components taking into account K_i was calculated from the formula

$$\lambda = \lambda_{in}(\tau)^{\alpha-1}, \qquad (4)$$

where

$$\alpha = 0.5e^{K_i} = 0.5e^{f(K_1,K_2,K_3,K_4,K_5)}. \qquad (5)$$

To estimate the influence of each coefficient in (5), the values of K_i were calculated from the formula

$$K_i = \ln\left(2\alpha'\right), \qquad (6)$$

where α' is the coefficient that takes into account the specific features related to assembling and operation of the segment.

The failure rate of each (ith) faulty segment was calculated from the formula

$$\lambda_i = \frac{1}{8760\tau_i L_i}, \qquad (7)$$

where L_i is the length of segment pipelines, km.

After that, the coefficient α' was determined using the expression obtained by transforming formula (4)

$$\alpha' = \frac{\log\left(\lambda_i/\lambda_{in}\right)}{\log\left(\tau\right)} + 1. \qquad (8)$$

Having the values of the K_i coefficient calculated in advance, it is possible to estimate the influence of additional factors on the failure rate of heat network segments. The influence of one or another parameter was estimated by groups of failures united by a common factor (a group of factors).

At the first stage, we analyzed a selected group of failures united by a single parameter, namely, the residual pipeline wall thickness δ_{res} or the wall thinning K_1. The wall thinning was calculated from the formula

$$K_1 = \left(1 - \frac{\delta_{res}}{\delta}\right)100\%, \qquad (9)$$

where δ is the initial pipeline wall thickness.

The numerical figures given below show the comparison between the wall thinning and the experimentally obtained value of the coefficient K_i:

K_1, %	K_i
11.1	1.02
12.5	1.05
20.0	1.08
27.5	1.13
34.3	1.20
40.0	1.23
52.5	1.29
54.3	1.33
62.5	1.37

The dependence of the coefficient K_i that takes into account additional factors on the pipeline wall thinning is shown in Fig. 1a and can be represented by the equation

$$K_i = 0.00673K_1 + 0.954. \qquad (10)$$

Since all remaining cases of the heat network's component failures include the parameter K_1, the influence of the other parameters is only determined by the slope of linear dependence (10).

At the next stage, we analyzed the selected group of failures including two additional factors, namely, the thinning of pipeline wall metal (K_1) and soil corrosiveness (K_3):

K_1, %	K_i
24.7	1.13
25.0	1.15
37.5	1.19
60.0	1.37

In the overall amount of statistical information, we revealed a single case of segment failure that occurred as a result of a combination of three parameters (K_1, K_2 and K_3), for which K_i = 1.13. The functional dependence of the coefficient K_i on the parameters K_1 and K_3 is shown in Fig. 1b and is expressed by the formula

$$K_i = 0.00664K_1 + 0.964. \qquad (11)$$

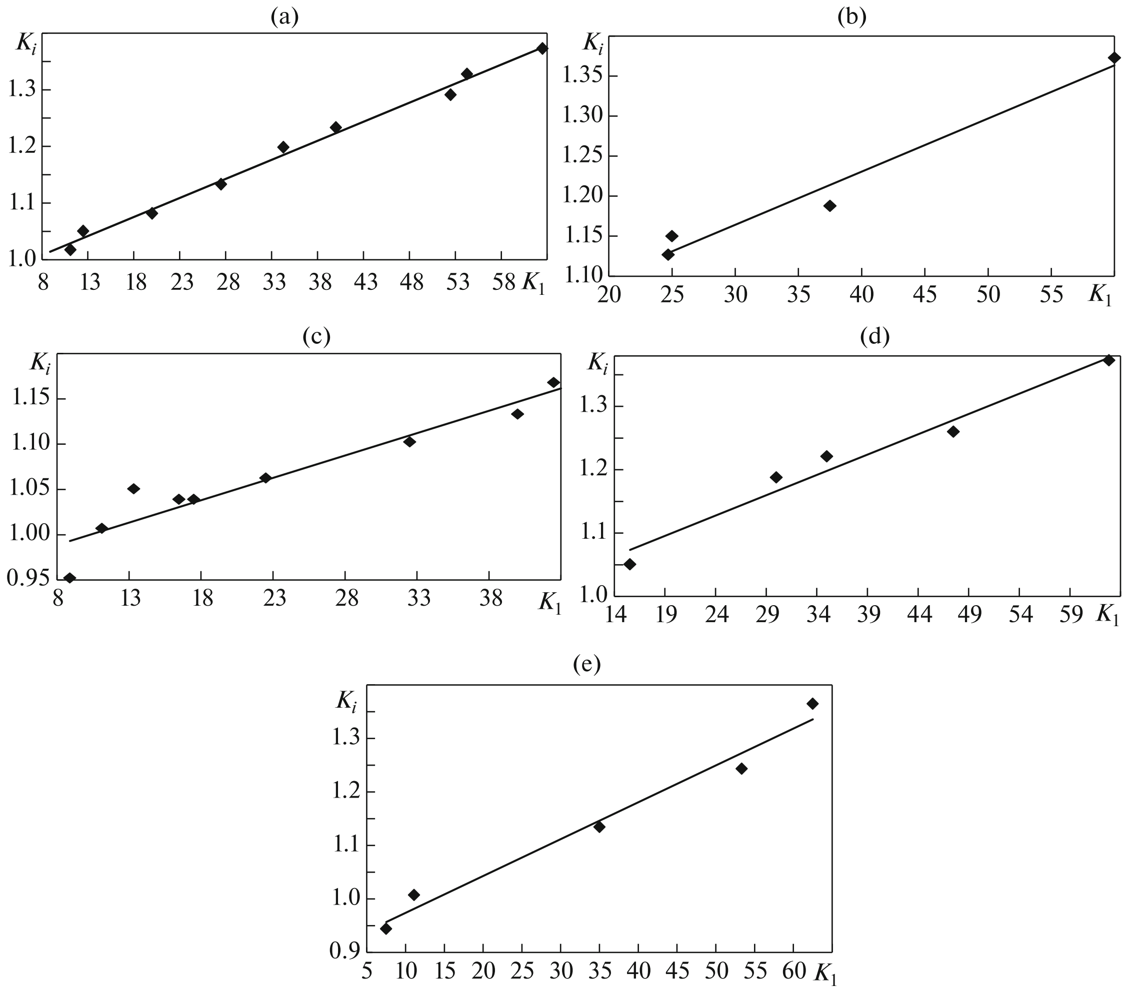

Fig. 1. Influence of additional parameters on the coefficient for accounting them. Additional parameters: (a) K_1; (b) K_1, K_3; (c) K_1, K_4; (d) K_1, K_5; (e) K_1–K_5.

The selection of failures is given below, including the pipeline wall thinning (K_1) and conduit flooding (flooding traces) (K_4):

K_1, %	K_i
8.9	0.95
11.1	1.01
13.3	1.05
16.5	1.04
17.5	1.04
22.5	1.06
32.5	1.10
40.0	1.13
42.5	1.17

The functional dependence of the coefficient K_i on the parameters K_1 and K_4 is shown in Fig. 1c and is represented by the formula

$$K_i = 0.00494K_1 + 0.949. \quad (12)$$

The next selection includes the pipeline wall thinning (K_1) and pipeline intersection with utility lines (K_5):

K_1, %	K_i
15.6	1.05
30.0	1.19
35.0	1.22
47.5	1.26
62.9	1.37

The functional dependence of the coefficient K_i on the parameters K_1 and K_5 (Fig. 1d) is given by

$$K_i = 0.00641K_1 + 0.973. \quad (13)$$

In the final selection of failures, we included five factors at once: the pipeline wall thinning (K_1), the other (previous) bursts in the segment (K_2), the soil corrosiveness (K_3), the conduit flooding (flooding

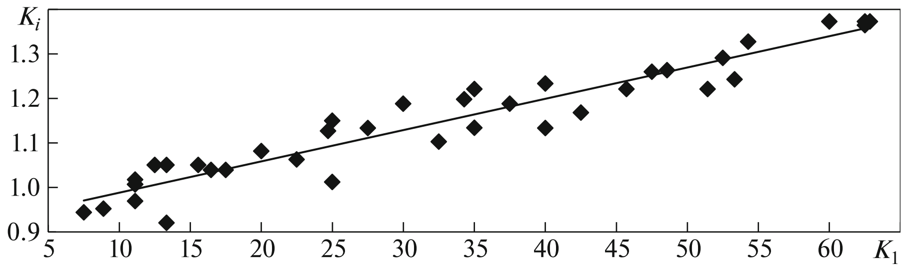

Fig. 2. General functional dependence on all cases of a heat network's segments' failures.

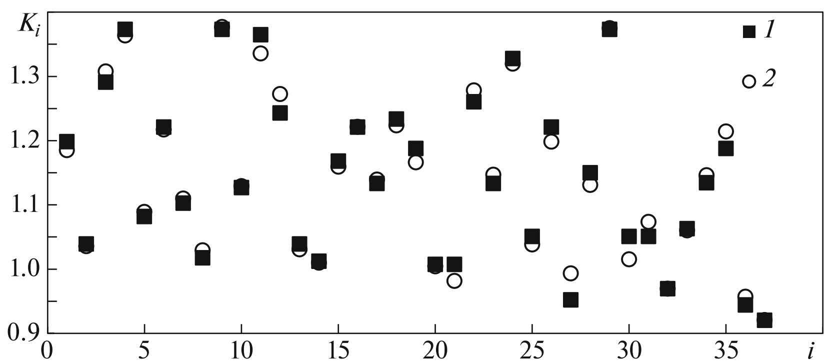

Fig. 3. (*1*) Theoretical and (*2*) experimental values of the additional parameters' accounting coefficient.

traces) (K_4), and pipeline intersection with utility lines (K_5):

K_1, %	K_i
7.5	0.94
11.1	1.01
35.0	1.13
53.3	1.24
62.5	1.36

The functional dependence of the coefficient K_i on the parameters K_1, K_2, K_3, K_4, and K_5 is shown in Fig. 1e and can be represented by the equation

$$K_i = 0.00689K_1 + 0.905. \quad (14)$$

The remaining single cases of a heat network's segments' failures (e.g., the combinations K_1–K_2, K_1–K_3–K_5, etc.), which were not included in one or another selection, were taken into account by the general functional dependence constructed from all experimental values of the coefficient K_i (Fig. 2)

$$K_i = 0.00704K_1 + 0.918. \quad (15)$$

Based on functional dependences (10)–(15), we calculated the theoretical values of the coefficient K_i presented in [13].

For comparison, Fig. 3 shows the theoretical and experimental values of the coefficient K_i that takes into account additional parameters. As is seen from the graph, the theoretical parameters deviate from the experimental data by no more than 1.13%. As an example illustrating the procedure for calculating the experimental and theoretical values of the coefficients K_i, Table 1 gives the statistical data on damages in heat networks and the calculation results.

CONCLUSIONS

(1) It has been established, based on the analysis of factors influencing the failure rate of heat network pipelines, that there are factors which, although having not been included in the existing evaluation procedure, still have an essential effect on heat supply reliability: the pipeline wall thickness, bursts in the heat network segment, soil corrosiveness, conduit flooding, and intersection with utility lines.

(2) Comparison between the experimental data and results of determining the heat network reliability according to the developed calculation procedure and algorithm taking into account the influencing factors

Table 1. Data on steel pipeline bursts in the heat network segments in the city of Kazan commissioned before 1989 and the calculated values of the coefficient for taking into account additional parameters

Parameter	Segment number		
	1	2	3
L, m	85	190	90
d, mm	50	100	100
τ_{rep}, h:min	0:40	7:10	0:50
δ, mm	3.5	4.0	4.0
δ_{res}, mm	2.3	3.3	2.8
Wall thinning, %	34.3	17.5	30.0
Other bursts		Now	
Soil corrosiveness		Low	
Flooding	No	Yes	No
Intersection with utility lines	No	No	Yes
Additional parameters considered in the analysis:			
K_1	+	+	+
K_2	–	–	–
K_3	–	–	–
K_4	–	+	–
K_5	–	–	+
λ, 1/(km h)	4.974×10^{-5}	2.225×10^{-5}	4.698×10^{-5}
α	1.66	1.41	1.64
K_i:			
experimental	1.185	1.035	1.166
theoretical	1.198	1.039	1.188
ΔK_i	0.013	0.003	0.022
$\Delta\varepsilon$, %	1.128	0.329	1.871

d is the pipeline diameter; τ_{rep} is the burst repair time; ΔK_i is the deviation of the theoretical value from the experimental one; $\Delta\varepsilon$ is the error of the K_i calculation procedure.

coefficient has confirmed the adequacy of the proposed procedure.

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REFERENCES

1. *RF Federal Law of 27.07.2010 No. 190-FZ* "On Heat Supply*"*.
2. *RF Ministry of Regional Development Order of 26.07.2013 No. 310* "On approval of guidelines for the analysis of indicators used to assess the reliability of heat supply systems*"*.
3. *RF Government Decree of 16.05.2014 No. 452* "On approval of the rules for determining the planned and calculating the actual values of indicators of reliability and energy efficiency of heat supply facilities, as well as access to the specified milestones corresponding to the planned values from the subjects engaged in regulated activities in the heat supply system, and on amending the resolution of the government of the Russian Federation of May 15, 2010 No. 340*"*.
4. *Joint Order of the RF Ministry of Energy and RF Ministry of Regional Development No. 565/667 of 29.12.2012* "Guidelines for the development of heat supply schemes".
5. R. Barlow and F. Proschan, *Statistical Theory of Reliability and Life Testing* (Holt, Rinehart and Winston, New York, 1981; Nauka, Moscow, 1984).
6. *MDK 4-01.2001. Guidelines for the Technical Investigation and Registration of Technological Violations in the Systems of Municipal Energy Supply and the Work of the*

Energy Organizations of the Housing and Utilities Complex (GUP TsPP, Moscow, 2001).

7. B. V. Gnedenko and I. N. Kovalenko, *Introduction to Queuing Theory* (Nauka, Moscow, 1987; Birkhäuser, Boston, MA, 1989).
8. *Reliability of Energy Systems and Their Equipment: Handbook*, Vol. 4: *Reliability of Heat Supply Systems*, Ed. by Yu. N. Rudenko (Nauka, Novosibirsk, 2000) [in Russian].
9. E. V. Sennova, S. N. Kiryukhin, and A. O. Shimanskaya, "Methodology and algorithm for calculating the indicators of reliability of heat supply to consumers and reservation of heat networks in the development of heat supply schemes," Nov. Teplosnabzh., No. 12, 11–19 (2013).
10. V. A. Stennikov and I. V. Postnikov, "Development of methods for analyzing the reliability of heat supply," Izv. Vyssh. Uchebn. Zaved. Probl. Energ., No. 5–6, 28–40 (2010).
11. I. V. Postnikov and V. A. Stennikov, "Ensuring parametric reliability of heat supply systems," Izv. Vyssh. Uchebn. Zaved. Probl. Energ. **19** (3–4), 20–30 (2017).
12. I. V. Postnikov, V. A. Stennikov, E. E. Mednikova, and A. V. Penkovskii, "A methodology for optimization of component reliability of heat supply systems," Energy Procedia **105**, 3083–3088 (2017).
13. I. G. Akhmetova, *The System of Comprehensive Assessment and Improvement of Efficiency of Centralized Heat Supply of Housing and Public Utilities and Industrial Enterprises*, Doctoral Dissertation in Engineering (Kazan State Power Engineering Univ., Kazan, 2017).
14. I. P. Gaidyshev, *Solving Scientific and Engineering Problems using Excel, VBA and C/C*++ (BKhV-Peterburg, St. Petersburg, 2004) [in Russian].

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