Original Research Article:
full paper

(2022), «EUREKA: Physics and Engineering»
Number 2

DEVELOPMENT OF STATISTICAL MODELING OF THE PIPELINES' RELIABILITY PROJECTIONS OF THE MAIN HEAT NETWORKS, ACCORDING TO THE PERIOD OF OPERATION AND DIAMETER

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Abstract

Using the method of statistical modeling of pipeline reliability, the statistical model for forecasting the dependence of the failure parameter of pipelines of main heating networks on the service life and diameter was developed and analyzed. This method includes two techniques. The first allows to obtain predictive dependences of pipeline reliability indicators for systems that include sections of different diameters with different service life periods and actual data on damage over several years. The second increases the correctness of the obtained dependences by optimizing the service life step in the study of damage to heat pipes. As a result of the study, the dependence of the reliability of main pipelines on the service life and diameter was established. The condition and forecast values of the specified indicator of reliability of main heat pipelines, and also dynamics and range of its changes are defined. The average value of the failure rate parameter increases from 0.23 1/km year (diameter 300 mm) to 0.62 1/km year (diameter 800 mm), which is 2.7 times larger than the pipes with the diameter 300 mm. The multiplicity of changes in the value of the parameter of the flow of failures was also established in accordance with the change in the diameter of the pipelines. According to the developed statistical model the dependence for calculation of the forecast of quantity of damages of the main heat pipelines according to their service life, diameter and length is established. This will increase the reliability of heating systems and effectively plan the cost of material, technical and labor resources. The given method can be used to assess the forecast of the reliability of pipelines, respectively, of their diameters for other engineering systems and networks.

Keywords: statistical modeling, forecast, reliability, pipelines, diameter, analysis, main heat networks.

DOI: 10.21303/2461-4262.2022.002302

1. Introduction

The district heating system, which includes the energy source, consumers and heating networks, can provide the population with heat energy and hot water.

Main heat networks along with distribution provide transportation of the heat carrier to consumers. In this case, the reliability of main heat pipelines must be higher than the reliability of distribution.

The reliability of heating networks mainly depends on the reliability of pipelines, which in turn depends on the quality of construction and installation work, operation, as well as on the geometric characteristics – diameter and thickness of pipes.

To assess the condition and predict the reliability of heat pipelines in order to effectively plan the costs of pipes during the operation of heating networks, it is necessary to take into account their diameter.

The latter is possible on the basis of determining the forecast of the dependence of the reliability of the pipelines of the main heating networks on the service life and diameter, as the main indicator of the geometric characteristics of the pipes, structurally related to the wall thickness of the pipes.

Therefore, in the design, reconstruction and repair of heating networks, including mains, one of the most important technical and economic tasks is to determine the impact of the diameter of heat pipelines on their reliability.

Using the methods of exponential equalization, ARIMA, estimation of the trend of the homologous period and seasonal indicators based on statistical data on the frequency of damage to heating networks, the method for predicting failures in district heating systems has been developed [1]. This method (approach) requires the collection and analysis of data on damage over the long term (10 years) and requires the construction of as many as four models, which complicates its use.

In paper [2], the estimation of the probability of failure of district heating pipelines includes three types of analysis: probabilistic mathematical, deterministic thermohydraulic and complex deterministic-probabilistic analysis of the integrity of structures. This analysis is performed on the basis of data on the most damaged pipeline, which does not allow to correctly assess the reliability of the pipeline system as a whole.

The analysis of damage to heating networks presented in paper [3] requires a significant period of observations from 2003 to 2012 and did not determine the forecast of reliability of heating networks.

In paper [4], three groups of factors that cause wear of pipelines of central heating systems were considered, namely physical, environmental and operational. Recommendations for preventing damage to pipelines are given. However, in the work accustomed to the problem of reliability of pipes connected to the central heating system, there are no values of reliability of pipes, their dynamics and forecast.

In paper [5], the failures of district heating systems are determined in accordance with the heat output and the temperature of the outside air. The disadvantage of this technique is the lack of forecasting the reliability of the system.

The methodology for determining the optimal parameters of the reliability of the components of the heat supply system is based on the methods of the theory of hydraulic circuits, nodal indicators of the reliability of heat supply, Markov models of random process and general patterns of cogeneration and heat transfer processes [6]. The disadvantages of this methodology are the presence in its composition of several methods and the lack of ability to predict the reliability of heating systems.

According to the method of analysis of damage to pipelines [7] is determined by the forecast of reliability of pipelines depending on the service life. However, this paper does not indicate the possibility of forecasting the reliability of pipelines from the service life and other parameters, for example, diameter, purpose of damage types and their corresponding combinations.

As for the influence of the diameter of pipelines, in paper [8] it is indicated that the parameter of the failure flow increases with the increase in the diameter, and in paper [9] – vice versa.

Thus, according to the literature review, it is advisable to improve the method of analysis of damage to pipelines, as well as to clarify the impact of diameter on their reliability.

The aim of research is to predict the reliability of pipelines of main heating networks from the service life and diameter. This will allow to calculate the number of current and projected damage to pipelines of appropriate diameters.

To do this, the following must be performed:

1. To improve the detection methodology of pipeline damage.
2. To obtain the dependence of the forecast of the parameter of the flow of failures of pipelines of main heating networks on the service life and diameter.
3. To set the multiplicity of increase of the failure flow parameter when increasing the diameter of heat pipes.
4. To determine the ranges of change in the parameter of the flow of failures, depending on the service life and diameters of heat pipes.
5. To obtain the dependence for calculating the forecast of the number of damages of main heat pipelines according to their service life, diameter and length.

2. Materials and methods

Due to the fact that the influence of geometric parameters (the diameter and thickness of the pipe walls) on the reliability of heat pipelines is twofold, namely: the increase in the diameter (lateral surface of pipes) leads to the decrease in reliability, and the wall thickness increases reliability, the resulting effect will be the effect of the ratio of the diameter to the thickness of the walls, since they are structurally connected with each other.

On the other hand, the ratio of pipe diameter to wall thickness, both for pipes of the same diameter and for pipes of different diameters is not the same value and it is almost impossible to take into account this ratio for the system with pipelines of different diameters and thicknesses.

In addition, this technique eliminates the possible difference in the thickness of the pipes of the same diameter, which could occur in the conditions of mass construction or repair work.

Fixation of damages of heat pipelines is also correlated with their diameter, and in the studies of reliability of heat pipelines, diameters of pipelines generally appear.

In connection with the above, for the convenience of using the calculated dependencies, it is advisable to use the pipe diameter as the design parameter.

As the indicator of reliability taken: the parameter of the failure rate is ω (1/km year).

In the general case, for the pipeline system, sections of which have different lengths, diameters, year of construction and data on damage over several years, it is possible to determine the dependence of the average value of the failure flow parameter. The average value of the parameter of the flow of failures from the service life for the significant period of operation exceeds the number of years of taking readings is determined according to the methodology [7]. The method is that due to the availability of data on the damage of pipelines for several years and the need to obtain the dependence of reliability indicators for long-term operation, the average failure rate parameter ω is calculated, defined as the weighted average for sections of pipelines included in this system, which had different commissioning dates and for which there are values of the number of damages over several years.

To level the influence of climatic factors for the small period of research and the possible absence of some sections of the construction networks of individual years, it is advisable to use the method [10], according to which the optimal discrete service life is 3 years.

In this case, the value of the failure rate parameter obtained by the above method is observed for three years according to the method [9] and, subsequently, this value is used to obtain statistical models. Thus, the set of indirect values of the failure flow parameter and the corresponding values of the service life of heat pipelines for the period from 9 to 36 years of operation is formed.

The obtained statistical model of the dependence of the flow parameter of failures on the service life of the pipeline system with different commissioning periods and damage statistics after several years allows predicting the reliability of pipelines for sections whose service life is less than the period outlined by the statistical model, and for long-term forecasting of the reliability of the entire system generally.

To obtain statistical models of the dependence of the forecast of the reliability of pipelines of main heating networks on the service life and diameter, the method of analyzing the damageability of pipelines [7] is used, which is supplemented by the argument – diameter.

Experimental data on damage are presented in the form of a matrix, for each diameter of heat pipes according to service life.

In this case, under the conditions of statistical modeling of the forecast of reliability of pipelines of main thermal networks according to service life and diameter, damages are defined for each site according to diameter of its pipelines separately by the following formula:

$$\omega \cdot \varnothing \cdot av \cdot (Tk) = \left\{ \begin{matrix} \text{not defined if } m_k = 0 \\ \text{(no observations)} \\ \dfrac{\sum_{i=1}^{m}\sum_{j=1}^{c}\delta\left(T_{ki} + j - T_k - 1\right)n_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{c}\delta\left(T_{ki} + j - T_k - 1\right)L_i} \text{ if } m_k \neq 0, \end{matrix} \right\}, \quad (1)$$

where $T_k = Tk_{min}$, Tk_{max};

$$\omega_{\varnothing ij} = \frac{n_{ij}}{L_i}. \tag{2}$$

$\omega_{\varnothing ij}$ – density (by years) of the flow of failures in i section for the *j* consecutive year of taking readings; $\omega_{\varnothing av}(Tk)$ – average for all observations density (by years) of the failure rate for the current *Tk* year of operation; *i* – site number; $i=1, m$; *m* – the number of sites; L_i – length of the i section; $L_i(\varnothing_1)$, $L_i(\varnothing_2)$, $L_i(\varnothing_{n\varnothing})$ – length of *i*-th section of pipelines with the diameter, respectively ($\varnothing_1$), ($\varnothing_2$)…, ($\varnothing_{n\varnothing}$), and

$$L_i = L_i(\varnothing_1) + L_i(\varnothing_2) + ... + L_i(\varnothing_{n_\varnothing}), \tag{3}$$

$n_i(\varnothing_1)$, $n_i(\varnothing_2)$, $n_i(\varnothing_n)$ – the number of damages, respectively, diameters and:

$$n = n_i(\varnothing_1) + n_i(\varnothing_2) + \ldots n_i(\varnothing_{ni}),$$

ti – calendar year of construction (commissioning) of *i* site; t_1 – the first calendar year of taking readings on damage of heat pipes; *j* – serial number of the year of taking readings; $j=1, s$; *c* – the number of years of taking readings; $tj = t_1 + j - 1$ – current calendar year of taking readings on damage of heat pipes; *Tki* – period of operation of i section from the year of commissioning (year of construction) before the year of the beginning of taking readings: $Tki = t_1 - ti$;

$$Tk_{min} = \overset{\min T_{\ddot{e}i}}{i = 1, m}; \; Tk_{max} = \overset{\max T_{\ddot{e}i}}{i = 1, m}. \tag{4}$$

Tk – calculated period of operation: $T_k = Tk_{min}, Tk_{max}$; m_k – the number of areas where the reading is taken for damage in *Tk* – year of operation, if $m_k = 0$, then for *Tk* year of operation there is no data on the damage of heat pipes; *nij* – the number of failures on *i* section in *j* consecutive year of taking readings; δ_{ij} – Kronecker symbol.

Methods of applied statistics, in particular, regression, correlation and variance analysis, and the theory of random processes and reliability are used to process data on the damageability of pipelines of heating networks. The damage model, which describes the functional dependence of the studied reliability indicator on the time and design parameters, is formed in the form of the regression ratio. The quality of modeling is checked by statistical criteria that reflect the adequacy of the regression model and the significance of its coefficients, and is confirmed by analysis of the results of computational experiments. The measure of the adequacy of the regression is Fisher's F-statistic, and the significance of each regression coefficient is determined by Student's t-statistic.

The object of research is the pipelines of the main heat networks of the Municipal Enterprise «Kharkiv Heat Networks» (https://www.hts.kharkov.ua/, Ukraine).

To obtain statistical models of indicators of the reliability of heating networks, let's use data on the damageability of the main heat pipelines of the Municipal Enterprise «Kharkiv Heat Networks» (https://www.hts.kharkov.ua/, Ukraine) for the period 2003–2005, ∅ 300–800 mm, length 437.9 km, built in 1968–1996, laid in underground impassable, semi-conductive, pass-through channels and using the above-ground installation method, using the techniques given above.

The forecast of dependence of the parameter of the flow of failures on the service life of the repaired pipelines is obtained based on the results of specific damage to the pipelines in accordance with the above method and is the basis for obtaining the dependences of other reliability indicators.

Fig. 1 shows the graphical dependences of the parameter of the flow of failures from the service life of pipelines of main heating networks and their diameter.

Fig. 1 shows that the nature of the dependence of the parameter of the flow of failures of pipelines of all diameters on the service life is identical and represents a family of S-shaped symmetric curves with the same values of the extreme points, which divide the dependencies into three periods:

I period – the increase in the parameter of the flow of failures from 9 to 26 years due to the impact of destructive factors in the places of their intensive action;

II period – the decrease in the parameter of the flow of failures in the period from 26 to 29.5 years, which is explained by the overhaul of the most sophisticated sections of pipelines;

III period – the sharp increase in the parameter of the flow of failures from 29.5 to 36 years and probably in the future due to the sharp decrease in the wall thickness of pipes during corrosion and the increase in the influence of the coolant pressure.

It also follows from **Fig. 1** that with the increase in the diameter of pipelines of main heating networks, the parameter of the failure flow increases.

On the basis of experimental data, the statistical model of the forecast of dependence of parameter of the flow of failures $\omega_{\varnothing}$ on service life t and diameters $\varnothing$ of pipelines of the main heat networks is developed:

$$\omega_{sh}=\begin{pmatrix}0.08515t-0.001443t^2+0.00001766t^3+\\+0.7054\dfrac{1}{1+0.1|t-27|}-1.732\dfrac{1}{1+0.1|t-29|}\end{pmatrix}\cdot(D/1000). \quad (5)$$

The influence of the pipeline diameter and its wall thickness on the dynamics of the failure flow parameter is twofold. On the one hand, with the increase in the diameter, the wall thickness mainly increases, and at the constant corrosion rate, the crack appearance time increases.

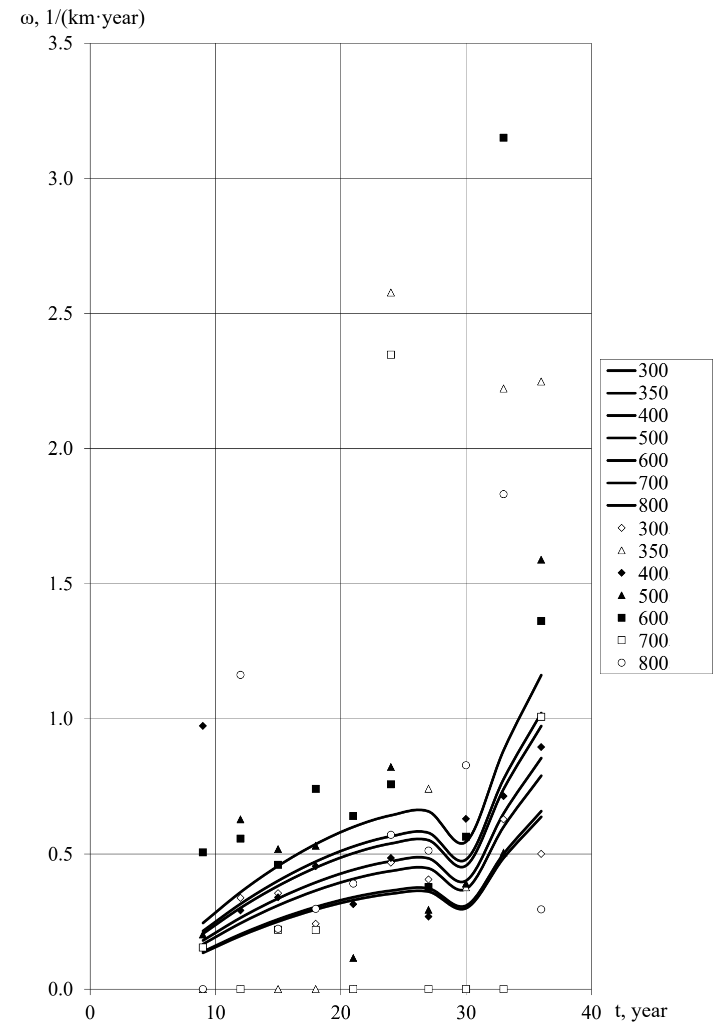

Fig. 1. Dependence of the parameter of the flow of failures on the service life of pipelines and their diameter (cross sections by diameters): 1 – 300 mm; 2 – 350 mm; 3 – 400 mm; 4 – 500 mm; 5 – 600 mm; 6 – 700 mm; 7 – 800 mm

On the other hand, with the increase in the diameter, the lateral surface of the pipeline increases, and, accordingly, the likelihood of ulcers, which in turn, with intense corrosion and poor-quality pipe material, can significantly accelerate the process of cracks.

In addition, at the same coolant pressure, its mechanical action on ulcers is greater at the larger diameter, which reduces the time of fistula.

3. Results and discussion

The resulting effect of the influence of these trends on the rate of occurrence of cracks, and, accordingly, on the parameter of the flow of failures depends on the high-quality manufacture of pipes, the quality of construction work and operating conditions, both from the inside of the pipeline and from the outside.

As can be seen from **Fig. 1** duration of the I period of operation makes 17 years, II and III respectively 3:5 and 6:5 years.

The duration of the first period of operation is explained by the significant intensity of the destructive factors in the places of their greatest action, with the slight decrease in their thickness of the pipes of the main number under the action of corrosion.

Places of intensive action of destructive factors are characterized by the presence of electrochemical corrosion in places of electric vehicles and electrical networks, partial depressurization of channel seams and getting into the channels of water, silt, mechanical damage to insulation during ground laying of pipelines, etc.

The duration of II period of operation is determined by the duration of repair work to replace the most damaged sections of heating pipes.

The duration of III period of operation is due to the sharp increase in damage due to the critical change in the wall thickness of the pipes during long-term operation under the action of mainly corrosion.

Quantitative assessment of the influence of the diameter of the pipelines of the main heating networks on the value of the parameter of the flow of failures can be determined by the average values of the latter for the respective diameters.

The average values of the failure rate parameter for pipelines of main heating networks with diameters of 300–800 mm for the period of operation of 9–36 years are given in **Table 1**.

Table 1
Average values of the parameter of the failure rate of pipelines of main heating networks according to their diameter

Diameter of pipeline, mm	**300**	**350**	**400**	**500**	**600**	**700**	**800**
Failure flow parameter value, 1/km year	0.23	0.27	0.31	0.39	0.47	0.55	0.62

Table 1 shows that the average value of the failure rate parameter increases from 0.23 1/km year (diameter 300 mm) to 0.62 1/km year (diameter 800 mm), which is 2.7 times larger than the pipes with the diameter 300 mm.

Moreover, the average value of the failure rate parameter of each subsequent diameter increases by the average of 1.18 times compared to the previous one.

This can be explained by the predominant influence of the side surface (diameter) of heat pipes in comparison with the influence of their thickness on the value of the parameter of the flow of failures (damage).

The range of change of the parameter of the flow of failures of pipelines of main heating networks from the term of their operation is limited by the upper curve and corresponds to the pipeline with the diameter of 800 mm with extreme points 0.27, 0.68, 0.56, and 1.1 1/km year and the lower curve of the pipeline with diameter 300 mm and extreme points of 0.1, 0.26, 0.21 and 0.41 1/km year.

As can be seen from **Table 1** and **Fig. 1**, the value of the parameter of the flow of failures gradually increases with increasing diameter of the pipelines of the main heating networks.

These numerical values of the ratio of the average values of the failure rate parameter of adjacent heat pipes, as well as their maximum and minimum values show how much greater the impact on the damage has the side surface (diameter) of the pipes compared to the wall thickness.

The developed statistical model of the forecast of reliability of the main heat pipelines according to service life and diameters, besides definition of their reliability, can be used for calculation of the forecast of quantity of damages of the specified pipelines.

Using the dependence (2) and the specified statistical model (5) the following can be written:

$$n_{i\varnothing} = L_{i\varnothing} \cdot \omega_{\varnothing}, \tag{6}$$

or

$$n_{i\varnothing} = L_{ii\varnothing} \cdot \begin{pmatrix} 0.08515t - 0.001443t^2 + 0.00001766t^3 + \\ +0.7054\dfrac{1}{1+0.1|t-27|} - 1.732\dfrac{1}{1+0.1|t-29|} \end{pmatrix} \cdot (D/1000). \tag{7}$$

Thus, it is possible to calculate the forecast of the number of damages of pipes of main thermal networks for the specific year of operation for the specified diameter and length of the pipeline.

Comparison of the obtained results with those showed in the literature is the following.

In contrast to methods (1)–(5), as a result, improved methods (6) allowed to obtain statistical models of the dependence of the forecast of reliability of main heat pipelines on the service life and diameter for the period of 9–36 years of operation using damage data for three years.

Comparison of the obtained results with the literature data on the influence of the diameters of the heat pipelines of the main heating networks on their damageability showed the following.

The obtained results correlate with the results given in [9], i. e. with increasing the diameter of the pipelines, the failure flow parameter increases.

Reduction of specific damage of main heating networks is noted in [8]. This can be explained by the short observation period of operation of the pipelines.

According to the developed statistical model the dependence for calculation of the forecast of quantity of damages of the main heat pipelines according to their service life, diameter and length is established. This will increase the reliability of heating systems and effectively plan the cost of material, technical and labor resources. The given method can be used to assess the forecast of the reliability of pipelines, respectively, of their diameters for other engineering systems and networks.

4. Conclusions

Improved method of analysis of pipeline damage, which allowed to obtain statistical models for forecasting the dependence of the reliability of heat pipelines on two parameters of service life and diameter.

As a result of the analysis of the received statistical models it is established that: statistical model for forecasting the dependence of the parameter of the flow of failures on the service life and diameter is of the family of *S* – like symmetrical curves and includes three periods:

I – 9–26 years of increase of parameter of the flow of failures;

II – 26–29.5 years of reduction of parameter of the flow of failures;

III – 29.5–36 years, the sharp increase in the parameter of the flow of failures.

The average values of the failure parameter of the main pipelines with diameters of 300–800 mm for the period of operation of 9–36 years increase with increasing diameter from 0.23 to 0.62 1/km year.

The multiplicity of the increase in the parameter of the flow of failures corresponding to the increase in the diameter of the pipelines of the main heating networks is, on average, 1.18 times.

The range of variation of the parameter of the flow of failures for pipelines of main heating networks is: lower limit – 0.1; 0.26; 0.21; 0.41 1/km year (∅300 mm) and the upper limit – 0.27; 0.68; 0.56; 1.1 1/km year (∅800 mm).

The dependence for calculation of the forecast of quantity of damages of the main heat pipelines according to their service life, diameter and length is established.

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Received date 20.04.2021
Accepted date 20.02.2022
Published date 31.03.2022

How to cite: *Maliavina, O., Yakunin, A., Hrankina, V., Milanko, V. (2022). Development of statistical modeling of the pipelines' reliability projections of the main heat networks, according to the period of operation and diameter. EUREKA: Physics and Engineering, 2, 74–81. doi: https://doi.org/10.21303/2461-4262.2022.002302*