Model of damage accumulation in heat networks

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Abstract. The energy efficiency of heat networks is determined not only by heat losses, but also by the actual service life, since energy is also expended on the production of new pipes and the replacement of worn-out ones. The article describes the main characteristics of the state of the centralized heat supply system, which ensures the quality and safety of heat supply. Based on the analysis of existing models of physical wear of pipelines and equipment of heating networks, as well as the probability of their trouble-free operation, a mathematical model of damage accumulation has been proposed. The model presented in the article makes it possible to qualitatively describe the process of damage accumulation in heat networks as they are used.

1. Introduction

Currently, the energy efficiency of various sectors of economic activity is a key requirement of state policy. Energy-saving measures are important in the production and transfer of heat energy to the consumer, because the level of payments of the population for communal heating and hot water supply, which is one of the most significant in terms of expenditures of residents in the housing and utilities sector, depends on their efficiency. However, when implementing energy-saving technical solutions, one should take into account not only the effectiveness of the materials and products used, but also their durability. With the use of effective, but short-lived materials and products, the terms of capital repairs and equipment replacement are reduced. The cost of capital repairs of heating networks and the replacement of equipment in their composition can partially or fully compensate for the reduction in operating costs achieved through the use of more efficient, but less durable materials and products. Do not forget that the costs of reconstruction and repair of individual sections of the heating network are essentially energy costs: the production of new materials, fuel consumption for their transportation, the operation of machines and mechanisms in the areas under repair, the disposal of worn-out pipelines, etc. In this regard, not only the level of thermal energy losses during transportation of the coolant, but also indicators of the reliability of heat supply, as well as the durability of the elements of the centralized heat supply system (hereinafter referred to as CHS) should be referred to as energy efficiency criteria.

2. Reliability of heat supply
Reliability of heat supply is understood as a characteristic of the state of a system, in which the quality and safety of heat supply are ensured [1]. According to the requirements of SP 124.13330 [1, p. 6.25], the ability of centralized heat supply systems to ensure for a given time the required modes, parameters and quality of heat supply should be determined by three indicators (criteria): probability of trouble-free operation \( P \), availability factor \( A_F \) and survivability \( S \). As a given time, here it is necessary to understand the estimated service life of the individual elements of the system. In this regard, different service life can be set for different CHS elements. The reliability of heat supply is understood as a characteristic of the state of the system, which ensures the quality and safety of heat supply [1].

3. Lifetime of CHS elements
Consider what service life in the regulatory and methodological documents are assigned to the elements of CHS. According to the requirements of clause 7.1.2 of SP 30.13330 [2], piping of hot water plumbing systems should be made of pipes and fittings, whose service life at a temperature of 75 °C and a standard pressure is at least 25 years. In accordance with the requirements of paragraph. 10.2 and 10.3 SP 124.13330 [1] when designing heat networks, the estimated service life of steel, cast iron and non-metallic pipes must be at least 30 years. In accordance with the instructions of clause A.2 of GOST 30732 [3], the service life of insulated pipes and fittings with thermal insulation made of polyurethane foam with a protective sheath should also be at least 30 years.

Statistical analysis of technological violations of heating network equipment shows that the “characteristic lifetime of heat pipelines” in St. Petersburg, at which the probability of failure of heat pipelines in the centralized heat supply systems of the city reaches a value of 0.63, corresponds to 10 years [4], which is significantly less than the calculated indicators.

Due to the uncertainty of the concept of service life with a view to a more objective assessment of the degree of physical deterioration of CHS, the concept of the probability of its failure-free operation is considered. Under the probability of failure-free operation refers to the ability of the system to prevent failures, leading to a drop in temperature in heated premises of residential and public buildings below the standard [1]. At the same time, in accordance with the requirements of clause 3.2 of the joint venture 124.13330 [1], the minimum permissible indicator for the probability of failure-free operation for heating networks \( P_{TC} \) should be taken equal to 0.9. The analysis of failures in heat networks of St. Petersburg is presented in detail in [4]. The results of the study are graphically shown in [4]. If the probability of failure-free operation of CHS characterizes its reliability, then failures are the degree of physical deterioration of the system.

4. Model of damage accumulation (physical deterioration) of heat networks
To describe the process of damage accumulation in heat pipelines of heat networks, we introduce the following initial assumptions:
1. The design of heating networks is made in accordance with the requirements of the current regulatory documents (standards and sets of rules);
2. Construction of heat networks was performed in accordance with the requirements of the project documentation;
3. When delivered to the construction site, the heating network pipelines may have minor defects and damages that meet the product specifications, i.e. they have a margin of reliability, but somewhat lower compared to pipelines that do not have defects and damage in their composition;
4. During the installation of heating networks, some defects were made, the effect of which on the reliability of heat supply at the initial time point is insignificant;

Note. Introduction of assumptions 3 and 4 is due to the fact that with a significant supply of products to the construction site, as well as during their installation, it is impossible to fully ensure the full compliance of the supplied products and the production of works during their installation to regulatory requirements. The presence of accidents in the initial stage of operation of heating networks indicates the admissibility of such a statement. The latter means that at the initial moment of the operation of
networks the degree of their physical has some, non-zero, value $d_{\text{initial}}$. In existing models, these assumptions are usually not used.

5. As the operation of heat networks damages as a result of physical wear accumulate;

6. Damage accumulation rate over time $d_t'$ is proportional to their number $d_t$.

In this case, the damage accumulation model in heat networks with time will look like this:

$$d_t' = k \cdot d_t,$$

where $d_t'$ – damage accumulation rate;

$k$ – damage accumulation factor;

$d_t$ – amount of damage.

The solution to equation (1) is the following expression:

$$d_t = d_{\text{initial}} \cdot e^{kt},$$

where $d_t$, $k$ – same as equation (1);

$d_{\text{initial}}$ – the initial level of damage, numerically equal to the number of defects (or defective sections of heating networks) allowed during the installation of pipelines and equipment;

$t$ – time.

The value of the damage accumulation coefficient $k$ depends on the diameters of the pipelines, the thickness of the insulation layer, the conditions and modes of operation of thermal networks and, in general, can be set based on the analysis of data on failure statistics. Equation (2) describes an exponential damage growth model, which can only be true if there is an infinitely large margin in the reliability of heating networks or subject to the instantaneous repair of detected damages, which is fundamentally impossible. In real conditions of operation of heat networks, the amount of damage in them is limited to some of their critical levels $d_{cr}$, which characterize the exhaustion of the stock, resulting in a high probability of an emergency. Thus, the model in the form of (1) cannot reliably describe the actual processes of damage accumulation in heat networks.

In this regard, we introduce a number of additional assumptions, namely, we assume that:

7. With the accumulation of damage, the safety factor of the reliability of heating networks decreases, and the degree of their physical deterioration increases;

8. The degree of physical deterioration of heat networks is proportional to the amount of damage in them;

9. The amount of damage is limited to some critical level $d_{kp}$ at which the probability of an emergency reaching its maximum;

10. With the amount of damage $d_{cr}$, physical wear and tear reaches the maximum permissible value at which the condition of the pipelines of heating networks reaches an emergency level.

Taking into account additional assumptions, the model of physical deterioration of heat networks can be described by the following equation:

$$d_t = k \cdot d_t' \cdot (d_{cr} - d_t) ,$$

where $d_t'$, $k$, $d_t$ – same as equation (1);

$d_{cr}$ – the maximum amount of damage at which there is a probability of an accident on the heat network.

Solution (3) is an equation of the form:

$$d_t = \frac{d_{cr} \cdot d_{\text{initial}}}{d_{\text{initial}} + (d_{cr} - d_{\text{initial}}) \cdot e^{-kt}}$$

where: $d_t$, $k$, $t$ – same as equation (1);

$d_{\text{initial}}$ – same as equation (2);

$d_{cr}$ – same as equation (3).

After a series of transformations, equation (4) can also be represented as:
\[ d_t = \frac{d_{cr} + d_{\text{initial}} e^{kt}}{d_{cr} + d_{\text{initial}} (e^{kt} - 1)} \]  

where all designations are the same as in equation (4).

5. Damage accumulation model analysis

An equation of the form (4) is called logistic, and the function described by it is a sigmoid (in Figure 1).

![Figure 1. Damage accumulation model described by equation (4).](image)

The graph presented in Figure 2 shows that the model of damage accumulation under consideration is close to the asymptotically normal distribution. If the probability of failures in heat networks (\( \omega \)) is compared with the number of damage accumulated in them over time (\( d_t \)), then the graphs of the functions shown in Figure 2 (see the blue lines) will coincide qualitatively. In this regard, the model considered in the work may be of practical interest. Analysis of equation (4) shows the following patterns:

- at \( t = 0 \): \( d_t = d_{\text{initial}} \);
- back it is possible to establish that with \( d_{\text{initial}} = 0 \): \( d_t = 0 \), i.e. in the event that the pipelines and equipment of the heat supply networks do not have initial defects and during their installation no damage was also made, damage does not accumulate over time; This is a disadvantage of the presented model and explains the need to introduce assumptions 3 and 4;
- at small values of the operating time \( t \), an exponential growth of damage accumulation \( d_t \) is observed (the initial part of the curve in Figure 1);
- during long time of operation \( t \), the term \((d_{cr} - d_{\text{initial}}) e^{-kt}\) in the denominator of equation (4) tends to zero, i.e. \( d_t \) approaches the critical value of the damage \( d_{cr} \) amount indicator corresponding to the emergency state of the considered section of heating networks, and the damage growth function \( d_t = f(t) \) becomes close to linear.

From the analysis of equation (4) it also follows that with a constant damage accumulation factor \( k \), physical wear depends on the initial level of defects in the heating network \( d_{\text{initial}} \) (in Figure 2): the smaller \( d_{\text{initial}} \), the faster the system reaches the critical value of the quantitative measure of accumulated damage \( d_{cr} \).
Figure 2. Damage accumulation model in heat networks depending on the initial damage level $d_{initial}$ at a constant value of the coefficient $k$.

At the initial stage of operation of heating networks, damage can be caused by defects that were made during the installation of pipelines and equipment. And the more such defects are allowed, the more intense, according to equation (5), an increase in damage accumulation will be observed. Further damage caused by defects during installation will be caused by damage caused by aging, wear and external adverse effects. Over time, minor damage to local areas of the heat network can be combined into groups and become more significant. On the graph of accumulation of defects, this circumstance is reflected in the form of an increase in the angle of inclination of the curve to the abscissa axis (in Figure 1). When the critical level of damage in the network is reached $d_{cr}$, which characterizes the exhaustion of the reliability margin of the heat pipe, the risk of an emergency situation increases significantly. At the same time, the development of an accident is a probabilistic event, since depends on many factors.

The coefficient $k$ in this model characterizes the rate of damage accumulation and depends on the specific operating conditions of the system without taking into account the effects of improbable, critical in magnitude, impacts that are many times greater than the average statistical load on the system (for example, due to seismic effects). With a constant initial amount of damage $d_{initial}$, the higher the coefficient value $k$, the faster the system will reach the critical value of the amount of damage in the system $d_{KP}$ (in Figure 3). The rate of damage accumulation in the heat network depends on the operating conditions of the heat pipelines (the degree of water aggressiveness, the state of heat and waterproofing, etc.). Therefore, the angle of the graph can be used to estimate the quality of operation of the heat conductor.

Figure 3. Damage accumulation model in heat networks depending on the numerical value of damage accumulation factor $k$ at a constant value of the indicator $d_{initial}$.

It should be noted that heat networks operate in non-stationary conditions. The temperature and coolant flow rate in the system changes, periodic testing of heating networks is carried out. For this
reason, the deterioration of heating networks during the calendar year may occur unevenly. However, this unevenness with a long service life will be repeated regularly. In this regard, with the step of the estimated time interval equal to one year, the impact on the heat network can be considered almost regular. Timely repair work on emergency sections of the heating network can increase the term of their effective operation. Thus, the service life of the heat network can be extended due to the quality selection of materials and structures at the design stage, compliance with the requirements of project documentation and production technology at the stage of pipeline installation and organization of a system for scheduled preventive maintenance at the stage of operation of heat networks. The model presented in Figure 1 makes it possible to assess the current state of heating networks, and, in the presence of baseline data, predict their residual resource. The accuracy of predicting the residual resource of heat networks largely depends on the accuracy of the adopted calculation model. With the coincidence of the model and actual indicators of physical deterioration of heat networks, the model presented in the work will make it possible to establish a more efficient and economical procedure for the operation of the system for the maintenance and repair of heat networks. The model considered in the article was tested in relation to building structures [5–8] and reveals similarities with data obtained from processing and analyzing the results of field surveys [9].

6. Conclusion
The paper presents a model of damage accumulation in heat networks. An equation is obtained that qualitatively describes the dynamics of damage growth in pipelines depending on the operation time, on the basis of which their residual life can be estimated. It is shown that the energy efficiency of heating networks depends not only on the amount of heat energy losses in the networks, but also on their durability, since energy resources are spent not only on transporting the coolant to the consumer, but also on restoring and repairing emergency sections of the network that require energy to produce and deliver new products to the emergency section of the network, as well as to recycle old pipelines. The accuracy of the assessment of the residual resource depends on the correctness of the used calculation model of the physical deterioration of heat networks. The accuracy of predicting the residual life of individual sections of heating networks will make it possible to more rationally organize repair and restoration planning. The following main consequence follows from the damage accumulation model described in the work: the life of heat lines is the higher, the lower their initial damage level $d_{initial}$ and the coefficient of their accumulation rate $k$. Therefore, to reduce the accident rate of heating networks, it is necessary to use better materials, monitor the quality of installation work and reduce the degree of aggressiveness of adverse impacts on the network. The first two events will reduce the value $d_{initial}$, the last - to reduce the value of the coefficient $k$. After switching to closed heating systems, the specific number of emergency shutdowns on heat networks may decrease. According to the damage accumulation diagram, the angle of inclination of which depends on the numerical value of the parameter $k$ in the model, it is possible to assess the quality of operation of the heat pipes. In case of accelerated growth of damage in heat networks, it is recommended to take urgent measures to improve their operation modes. On existing networks, it is advisable to install dissolved oxygen analyzers and better control over the state of heating mains using the UEC system. When reconstructing emergency sections of heating mains with diameters up to 225 mm, it is advisable to use pre-insulated polymer pipelines with an anti-oxygen barrier. The last recommendation can be implemented only after optimization of the temperature schedules of regulation of heat supply.

7. References
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