Predicting the Condition of Heat Networks Sections Based on the Comparison of the Heat Transfer Model with the Thermography Data

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Abstract. With the enormous length of district heating networks, the need to restore heat pipelines is constantly increasing. Elimination of accidents requires much higher material costs than their prevention, therefore, timely detection of hazardous areas in an emergency relation and their replacement during preventive repairs is important. In this regard, it is necessary to predict the actual state of individual elements and the heat transportation system as a whole for the subsequent decision-making on its operational reliability. The aim of the work is to increase the reliability of heat supply systems by improving the method for predicting potentially hazardous sections of heat pipelines. The article presents a method of qualitative prediction of the state of underground heating mains, based on a comparison of heat losses calculated on the basis of thermography data with the values of heat losses determined from test data.

1. Introduction
The heat supply system of the Russian Federation as a part of the fuel and energy complex is the most important part of the national economy, which has a significant impact on the development of the economic and social spheres, as well as the environmental safety of the country. Today, the heat supply system of Russia is facing certain problems in the system of ensuring energy security. Overcoming these problems presupposes, among other things, a decrease in heat loss during the transportation of the heat conductor [1-3].

Losses of thermal energy in the heating networks of the Russian Federation amount to 10-20% (in some cases 30%) of the volume of generated thermal energy (with a standard of 5-7%), which is almost 4 times higher than in European countries [4]. There are almost no cases when the actual losses would not exceed the standard values. For the period from 2010 to 2018 in the country as a whole, there is an increase in this indicator by more than 1.5 times (figure 1) [4].

The total heat losses in the networks are about 450 million Gcal/year [5]. The savings potential due to progressive methods of thermal insulation, prompt elimination of leaks, reduction of pipe diameters, partial decentralization of heat supply to end consumers is about 300 million Gcal/year [5]. An increase in heat losses in comparison with the design values indicates a violation of the integrity of the building and heat-insulating structures of heat pipelines, followed by corrosive destruction of the steel pipe. Other reasons may be heat-transfer agent leaks, wetting of insulation and soil, etc.
Prediction of the actual state of individual elements and the heat transportation system as a whole in order to timely identify areas with a disturbed operating mode for subsequent decision-making on its operational reliability is an urgent task of energy conservation and environmental protection.

The issues of predicting the state of underground heating networks and reducing heat losses are widely reflected in domestic and foreign literature. The topic is widely studied, many scientists are engaged in it - Boguslavskiy L. D., Bushuev V.V., Denisov V.E., Ivanov V.V., Ignatiev V.K., Karimov Z.F., Kascheev V.P., Klyuchnikov A.D., Kovlyanskiy Ya.A., Lipovskikh V.M., Makarov A.A., Malafeev V.A., Marchuk G.I., Maslennikov G.K., Morton K.V., Pakshin A.V., Richtmayer R.D., Rodichev L.V., Tikhomirov A.L., Uat J., Umerkin G.H., Hall J. and others. However, due to the impossibility of accounting and analytical description of many factors affecting the process of wear of heat pipelines, at present the forecasting problem does not have a simple and accurate solution [6-8]. Therefore, the development of methods for assessing the state of pipelines of heating networks is relevant.

To study the thermal modes of operation of underground heating networks and monitor their condition, it is necessary to calculate the temperature fields and heat flows in the area of laying underground pipelines. Currently, a number of methods are used to determine the heat losses of underground heating networks (figure 2), the advantages and disadvantages of which are presented in figure 3 [7-11].

The performed analysis shows that the study of the phenomena of heat transfer in the area of the location of channel and channelless gaskets is far from completion and needs subsequent comprehensive study. In this regard, further development of theoretical methods of analysis, which would make it possible to effectively identify the main regularities of the operation of underground heating mains, is of great importance. Such methods, without replacing the experimental ones (testing processes), would make it possible to obtain more visible results, find relationships between operating parameters and provide the necessary information about the actual values of heat losses.
Figure 2. Systematization of methods for determining heat losses of underground heating networks.

Figure 3. Main features (advantages and disadvantages) of methods for determining heat losses of underground heating networks.
2. Materials and methods
Research methods included analytical generalization of known scientific and technical results, mathematical and physical modeling, numerical experiment and statistical data processing.

3. Results of the study
According to the authors, the thermal method of non-destructive testing (NDT method) is of particular interest for heat supply systems. The thermal NDT method is based on the registration of disturbances introduced by internal defects and anomalies into the reference character of the distribution of surface temperatures. The calculated temperatures on the soil surface for the typical operating modes of the network and the alleged defects are compared with the measured (actual) ones, and based on the comparison results, a conclusion is made about the state of the investigated section of the heating main [7].

The hardware base of thermal control is made up of infrared temperature measurement systems - thermal imagers. Thermal imaging diagnostics allows to quickly and reliably determine network sections with increased heat loss [7, 12], etc.

The basis of the theory of thermal control of underground utilities is the solution of problems of transfer in the zone of laying heating mains with assumed deep defects and anomalies.

The stationary temperature field in the channel walls and soil was found on the basis of the heat transfer equations:

\[ \text{div} [\lambda_{\text{channel}} (\text{grad} t_{\text{channel}})] = 0, \]  \hspace{2cm} (1)
\[ \text{div} [\lambda_{\text{soil}} (\text{grad} t_{\text{soil}})] = 0. \]  \hspace{2cm} (2)

At the boundaries of the outer surface of the pipes – the insulating layer, boundary conditions of the first kind were taken:

\[ t_{\text{insulation}, i} = t_{\text{pipe}, i}. \]  \hspace{2cm} (3)

On the contact surfaces of the insulating and cover layers, as well as on the outer surfaces of the channel walls and the soil, boundary conditions of the fourth kind were set:

\[ t_{\text{insulation}, i} = t_{\text{cover}, i} \quad \lambda_{\text{insulation}} \text{grad} t_{\text{insulation}, i} = \lambda_{\text{cover}} \text{grad} t_{\text{cover}, i}, \]  \hspace{2cm} (4)
\[ t_{\text{channel}} = t_{\text{soil}, i} \quad \lambda_{\text{channel}} \text{grad} t_{\text{channel}} = \lambda_{\text{soil}} \text{grad} t_{\text{soil}}. \]  \hspace{2cm} (5)

Boundary conditions of the third kind were used in the sections between the outer surface of the pipeline cover layers and the air in the channel, as well as between the air and the inner surface of the channel walls:

\[ -\lambda_{\text{cover}} \text{grad} t_{\text{cover}, i} = \alpha_{\text{cover}} (t_{\text{cover}, i} - t_{\text{air}}), \]  \hspace{2cm} (6)
\[ -\lambda_{\text{channel}} \text{grad} t_{\text{channel}} = \alpha_{\text{channel}} (t_{\text{air}} - t_{\text{channel}}). \]  \hspace{2cm} (7)

Boundary conditions of the third kind are taken at the boundary «soil surface – atmosphere»:

\[ \lambda_{\text{soil}} \text{grad} t_{\text{soil}} = \alpha_{\text{atmosphere}} (t_{\text{soil}} - t_{\text{atmosphere}}). \]  \hspace{2cm} (8)

At a sufficiently large distance from the gasket, the temperature gradients in the soil are equal to zero:

\[ \text{grad} t_{\text{soil}} = 0, \ x \to \infty; \ \text{grad} t_{\text{soil}} = 0, \ y \to \infty. \]  \hspace{2cm} (9)

For channelless pipelines, the mathematical description of the heat conduction process is simplified. So the heat transfer equation (1) for the channel walls drops out, and the boundary conditions (5), (6), and (7) are replaced by the relations:

\[ t_{\text{cover}, i} = t_{\text{soil}}, \ \lambda_{\text{cover}, i} \text{grad} t_{\text{cover}, i} = \lambda_{\text{soil}} \text{grad} t_{\text{soil}}, \]  \hspace{2cm} (10)

characterizing the conditions of conjugation at the boundaries of the surface of the «cover layer –
On the basis of the mathematical model of the heat exchange process in the system «heat pipelines – soil – atmosphere» for channelless laying and «heat pipelines – channel – soil – atmosphere» for channel, a computational program was created for calculating temperature fields and heat fluxes [7, 13-16]. The program allows to take into account the destruction of insulating layers on the supply, return, or simultaneously on both pipelines, flooding of the channel with network water, partial or complete destruction of the channel walls. Much attention was paid to the influence of insulation and soil moisture on the magnitude and nature of heat losses [7, 15-16].

For illustration, figure 4 [7] shows the results of a thermographic survey of heating networks in the Central District of Rostov-on-Don. The main feature of the selected channelless section is its long period of operation (about 10 years).

The surveys were carried out at the beginning of the heating period, when the water temperature in the supply pipeline was 50°C, and in the return – 35°C. The bold line shows the experimental (measured) thermogram (line 5). Here are the following cases: normal (design) operating mode (line 1); soil moistening by 30% (line 2); destruction of thermal insulation on both pipelines (line 3); lack of thermal insulation on both pipelines and soil moistening by 30% (line 4). As can be seen from the above graph, the experimental curve of the soil temperature above the gasket fluctuates around the 3 – line in the case of destruction of thermal insulation on both pipelines. The above assumptions were confirmed during the control openings of the investigated section of the heating network.

![Figure 4](image)

Figure 4. Results of thermographic inspection of heating networks in the Central District of Rostov-on-Don.

The disadvantage of the thermal NDT method is that, due to the presence of additive interference, the same distribution of surface temperatures can correspond to a different set of defects and anomalies. In this regard, the above-ground installation is characterized by the smallest number of possible violations that increase heat losses, and, therefore, the minimum interference. Next are the complex thermal insulation structures of underground channelless and, especially, channel heating mains [7].

4. Discussion and conclusions

The results of the performed inspection of the technical condition of the heat-insulating structures of the sections of heating networks using thermal imaging equipment were compared with the results of tests to determine the operational heat losses of water heating networks.
This made it possible to assess the reliability of the data for the quantitative determination of heat losses based on thermal imaging, using, as a kind of «standard», the results of thermal tests, which have maximum accuracy under these conditions.

The results obtained show that there is a satisfactory agreement between the values of heat losses found on the basis of thermal imaging and those determined as a result of tests. The discrepancies between the measured and calculated values of heat losses are in the range of 7.8-15.8%.

Thus, the thermal NDT method is one of the most effective ways to predict the condition of sections of underground heating mains.

5. References

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