Improving energy efficiency and reliability of heating networks through the use of multilayer thermal insulation structures

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Abstract. Thermal insulation of pipelines is actively used to reduce heat losses in heat supply systems, as well as to reduce the temperature on the utilities surfaces, for safety during daily operation. This method ensures uninterrupted operation of heating systems in the winter, eliminating the risk of the heat carrier freezing and, consequently, their failure. At the moment, the application of effective thermal insulation of heating network equipment and pipelines is of great importance. The lack of a high-quality heat-insulating coating on the pipeline surface leads to significant losses of fund from various level budgets and a decrease in the quality of the heat carrier, that is, its temperature. Special requirements are imposed on thermal insulation materials, according to current regulatory documents, compliance with which is monitored by specialized organizations. The thermophysical indicators study of modern heat-insulating materials of domestic production and their application impact on the efficiency of the heat supply system is an urgent task aimed at improving energy efficiency and reducing energy consumption by reducing heat losses in heating networks pipelines.

1. Introduction

One of the main problems of energy saving in Russia is the use of (poor-quality) low-quality heat-insulating materials in the pipelines construction of heating networks. This conclusion was made during the implementation analysis of the current energy strategy of Russia until 2020. Increased government funding for district heating has not produced the expected result, and this is confirmed by the adopted strategy for the development of Russia's energy sector until 2030 [1]. The implementation results of the energy strategy measures for the period up to 2020 were found to be «unsatisfactory», since there was no planned heat losses reduction by 60% in the centralized heat supply system and an increase in heat energy production by 34% [2]. This fact is confirmed by statistics on the increase in depreciation of the main central heating systems up to 70% as compared to 65% for the period until 2010; 30% of heat losses occur in heat networks that require urgent overhaul (82%), and in some cases, complete replacement of the heating network sections; more than 70 damages occur per 100 km of the central heating system pipelines. It can be concluded from the above that the priority of the country's economic and energy policy is to improve the quality and reliability of the heat supply.
system, since it accounts for the majority of the financing. Heat losses reducing in heating networks due to application of high-quality modern heat-insulating materials will allow increasing the service life of pipelines and rational use of the energy potential, which is the main task of the energy strategy. The implementation of these measures will make it possible to achieve the set goals and reduce the tariffs for thermal energy.

Thus, the main task is to analyze the heat-insulating materials that contribute to the efficient and uninterrupted operation of heating networks.

2. Analysis of the heat network energy efficiency indicator and the thermal characteristics of thermal insulation materials

Energy efficiency of heating networks is a complex indicator, which is influenced by numerous factors [3-7]:

- heat losses through the outer shells of the heating networks pipeline structures, depending on the efficiency of thermal insulation;
- the amount of heat energy transferred from the heat source, which depends on the used equipment power and, therefore, the efficiency of the heat source, the combustion quality of the used fuel, and the associated amount of heat losses and the possibility of its reduction [8-10].

Consequently, the energy efficiency of Centralized Heating Networks is determined in accordance with the recommendations of [4] as follows:

$$\eta = \frac{\sum Q_c}{Q_v}.$$  

\(\sum Q_c\) – the amount of thermal energy received by consumers, W; \(Q_v\) – the amount of thermal energy transmitted from the heat source, W.

To ensure the reliability and efficiency of the heat supply system, when choosing a heat-insulating material, it is necessary to be guided by criteria such as thermophysical indicators and their change during the operation [11-15].

The most important indicators by which this or that heat-insulating material is selected for application on pipelines sections of the heating network are [16]:

- thermal conductivity coefficient;
- density;
- combustibility group;
- temperature operating mode.

Comparative characteristics of thermal insulation materials are given in Table 1 [17-20].

All considered materials comply with the modern standards requirements.

According to the thermal conductivity coefficient, four heat-insulating materials are the most effective: liquid ceramic insulation Re-Therm – 0.001 W/m·°C, PPU – 0.033 W/m·°C, Polyminal foam – from 0.035 W/m·°C and Rock wool. Of these, Re-Therm paint has the lowest thermal conductivity coefficient of 0.001 W/m·°C, however, this justly causes distrust among consumers, since the air thermal conductivity coefficient is 0.023 W/m·°C.

In terms of thermal conductivity coefficient, Re-Therm material is many times lower than polyurethane foam. In terms of durability, polyurethane foam thermal insulation is superior to Re-Therm, but lags behind in terms of combustibility, flammability, smoke-forming ability and toxicity. In addition, liquid insulation has a temperature operating mode much higher than PU-foam, which has a restriction on the application up to 130°C, while the heating network mainly has a temperature chart of 150°C/70°C. In economic terms, Re-Therm thermal insulation is twice as good as PPU thermal insulation, since additional expensive equipment and devices are required to apply PPU thermal insulation. Obviously, these two heat-insulating materials, PPU and Re-Therm, are the leaders. In this case, it is possible to expand the use of PPU material for heating networks with a temperature chart up
to 150°C/70°C due to the use of an additional thermal insulation layer, a layer between the pipeline and the PPU material.

### Table 1. Summary table of technical characteristics of thermal insulation materials.

| Material                  | Rock wool | PPU | Foam rubber | Polymineral foam | Re-therm | TTM-V |
|---------------------------|-----------|-----|-------------|------------------|----------|-------|
| Density, kg/m³            | 40–210    | 60  | 50–70       | 270              | 509      | 200–310 |
| Thermal conductivity, W/m°C) | 0.038–0.045 | 0.033 | 0.038–0.043 | 0.035–0.041 | 0.001  | 0.054  |
| Water absorption, %       | 12–30     | 1–3 | 1–3         | 0.5              | 3        | 15–50  |
| Vapor permeability, mg/(m·h·Pa) | 0.25–0.3  | 0.02–0.05 | 0.02–0.07 | 0.17            | 0.012   | 0.012  |
| Compressive strength, MPa | 4–60      | 0.2 | 1           | 1.2              | 2        | 2–5    |
| Combustibility group      | NG, G1    | G3–G4 | G1          | G4               | G1       | NG     |
| Flammability group        | V1        | V3  | V2          | V2               | V1       | –      |
| Smoke generating group    | D1        | D3  | D3          | D3               | D2       | D1     |
| Temperature operating mode, °C | from -60 to +400 | from 70 to +150 | from -50 to +110 | to +150 | from -60 to +250 | from -20 to +250 |
| Toxicity                  | T1        | T3  | T2          | T3               | T1       | –      |
| Longevity, years          | 50        | 30  | 25          | 30               | 15       | 15     |
| Price, rub / p. m         | 199       | 604 | 696         | 696              | 287      | 849    |

3. Analysis of the performed investigations results

Additional studies have been conducted on the value of the heat flux passing through the heat-insulating structure, consisting of the leading materials in a single and double-layer design - Re-Therm material, double-layer Re-Therm structure and mineral (rock) wool (figure 1), double-layer Re-Therm structure and PPU (figure 2).

The heat flux density, W/m, is determined by the formula [16]:

\[
q_i = \frac{t_i' - t_i''}{R_{li}} = 2\pi \lambda_{li} \frac{t_i' - t_i''}{\ln \left( \frac{d_{in}}{d_o} \right)}.
\]  

\(t_i'\) – the inner surface temperature of the insulation, °C; \(t_i''\) – the outer surface temperature of the insulation, °C; \(R_{li}\) – thermal resistance of the insulating layer, (m·°C)/W; \(d_{in}\) – outer diameter of the insulating layer, m; \(d_o\) – outer diameter of the insulated object, m.
To determine the heat flux through the insulation, the linear heat flux density must be multiplied by the parameter of the insulated surface. It is also necessary to take into account the additional heat flow through the supports, valves and other equipment of the heating network.

The heat flux through an insulated pipeline, $W$, is calculated by the formula [16]:

$$Q = q_i \cdot L_p \cdot (K_a \cdot L + \sum L_{additional}) \cdot$$  (3)

$L$ – actual length of the calculated section, m; $L_p$ – the estimated length of the pipeline taking into account additional losses, m; $K_a$ – coefficient taking into account additional heat flow through supports and hangers, is determined by reference data.

The heat flow calculation results are given in Table 2, which show that the application of a multilayer heat-insulating structure allows to reduce the heat flow from the supply pipe by 2.4–2.7 times, and from the return pipe by 1.3–1.7 times. The largest reduction in heat flux corresponds to a heat-insulating structure consisting of Re-Therm material and polyurethane foam (PPU).

The results of the research are clearly shown in figure 3.

4. Conclusion

The application of modern heat-insulating materials that meet the requirements of the regulatory literature allows to increase the efficiency and reliability of heat supply systems. The study results of the options for a multilayer, namely double-layer, heat-insulating structure, consisting of Re-Therm and PPU material, make it possible to expand the temperature limits of the most frequently used polyurethane foam material used for the production of pre-insulated pipelines in the factory and to reduce the heat flux passing through the considered construction by 63% for the supply pipe and by 42% for the return pipe and, therefore, to increase the energy efficiency of the heating network. They can also be used to develop the most effective pre-insulated pipeline system.
Table 2. Calculation of heat flux for single and double layer Re-Therm thermal insulation.

|                  | Re-Therm | Re-Therm and mineral wool | Re-Therm and PPU |
|------------------|----------|---------------------------|------------------|
|                  | supply   | return                    | supply           | return           | supply   | return           |
| $D$, m           | 0.273    | 0.273                     | 0.273            | 0.273            | 0.273    | 0.273            |
| $t_{in1}$, °C    | 90       | 50                        | 90               | 50               | 90       | 50               |
| $t_{in2}$, °C    | 35       | 31.16                     | 26.39            | 27.89            | 25.99    | 27.82            |
| $d_i$, (in), m   | 0.275    | 0.274                     | 0.373            | 0.356            | 0.309    | 0.297            |
| $L_{\text{additional}}$, m | 2.30     | 2.30                      | 2.30             |                  |          |                  |
| $L$, m           | 1        | 1                         | 1                |                  |          |                  |
| $K\text{n}$      | 1.15     | 1.15                      | 1.15             |                  |          |                  |
| $\lambda_{in1}$, W/m·°C | 0.001     | 0.001                   | 0.001            |                  |          |                  |
| $\lambda_{in2}$, W/m·°C | –        | 0.045                    | 0.033            |                  |          |                  |
| $q_i$, W/m      | 60.00    | 24.00                     | 25.22            | 15.82            | 22.20    | 13.75            |
| $Q$, W          | 207.01   | 82.81                     | 87.00            | 54.58            | 76.61    | 47.44            |

Figure 3. Comparison of single-layer and multi-layer thermal insulation construction.

Reference

[1] The energy strategy of Russia for the period until 2030: approved by order of the Government of the Russian Federation of November 13, 2009 No. 1715-r 2009 (Meeting of the legislation of the Russian Federation)

[2] The energy strategy of Russia for the period until 2020: approved by Decree of the Government of the Russian Federation of August 28, 2003 No. 1234-r 2003 (Meeting of the legislation of the Russian Federation)

[3] Kazakova E D and Biryuzova E A 2018 To the assessment of thermal insulation of pipelines (Ekaterinburg: Ural Federal University) pp 236–239

[4] SR 124.13330.2012 Heating network. Updated edition 2012 (Moscow: Standards Publishing) p 69

[5] Federal Law of July 27, 2010. No. 190 Federal Law "On Heat Supply"

[6] GOST 27.002-2015 Reliability in technology. Terms and Definitions (Moscow: Standards Publishing) p 15
[7] GOST 27751-2014 Reliability of building structures and bases. Main provisions (Moscow: Standards Publishing) p 22
[8] Biryuzova E A 2018 Investigation of methods for determining heat losses from external cooling of surfaces of a small-capacity hot-water boiler IOP Conf. Ser.: Mater. Sci. Eng. 463 032056
[9] Nefedova M A, Biryuzova E A, Pestich S D and Aleksandrov A S 2018 Comparative analysis of the efficiency of cast iron boilers at power plants IOP Conf. Ser.: Mater. Sci. Eng. 463 032047
[10] Biryuzova E A 2020 Investigation of Methods for Increasing of Energy Efficiency of Hot Water Boilers of Small and Average Capacity at the Expense of Reduction of Heat Losses with Exit Gases IOP Conf. Ser.: Mater. Sci. Eng. 753 022006
[11] Biryuzova E A 2019 Study of factors affecting reliability and efficiency of heat supply system IOP Conf. Ser.: Mater. Sci. Eng. 687 044028
[12] Raiser V D 1998 Reliability Theory in Building Design (Moscow: Publishing House of the Association of Building Institutions) p 304
[13] Belyaev Yu K (ed) 1985 Reliability of technical systems (Moscow: Radio and communications) p 356
[14] Baikov I R (ed) 2014 Analysis of methods for assessing energy-saving systems MIEE (Moscow) pp 121–132
[15] Semenov V G 2010 On improving the reliability and energy efficiency of heating networks Energosvet (Moscow) pp 71–79
[16] Designer's Handbook "Design of Thermal Networks" edited by A A Nikolayev 1965 (Moscow: Construction Literature Publishing House) p 359
[17] Razdobreeva A S and Biryuzova E A 2017 Energy saving in heat supply systems. Modern trends in the development of science and production West-Siberian Scientific Center (Kemerovo) pp 334–335
[18] Biryuzova E A 2013 Improving the energy efficiency of heat networks through the use of modern insulation materials Regional architecture and construction (Penza) 1 62–66
[19] Biryuzova E A 2014 Improving the energy efficiency of modern heat supply systems Efficient construction structures: theory and practice a collection of articles of the XIV International Scientific and Technical Conference. Edited by N N Laskova (Penza) pp 23–26
[20] Biryuzova E A, Glukhanov AS and Kobelev NS 2012 Application of modern pipeline systems in the design and reconstruction of heating networks Proceedings of the South-West State University Series Engineering and Technology (Kursk) 2-2 63–68