Methodology for calculating the ineffective diameter of thermal insulation

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Abstract. This article describes the results of energy efficiency analysis of various types of pipeline thermal insulation in a district heating system and equipment. The mathematical relations used in calculating the thickness of the thermal insulation for heat pipes and equipment are given. The concept of the critical value of the thermal insulation outside diameter of the heat pipe is described. An equation is presented that determines the ineffective thickness of the heat pipe insulation. A solution to this equation is proposed using numerical methods, namely, Newton's method. The results of calculations of ineffective thermal insulation diameters for various parameters of the coolant, the diameters of the pipeline itself, and various heat-insulating materials are presented. The obtained data are analyzed. Recommendations are given for the correct selection and calculation of the thermal insulation thickness of district heating pipelines, as well as for the reconstruction of the existing ones.

1. Introduction
Energy saving is one of the priority tasks not only in our country, but also in the whole world. In Russia, district heating systems are the main consumers of energy. Much attention is paid to solving the problems of energy-efficient consumption of thermal energy when creating the required microclimate parameters [1-6]. At the same time, the pipelines of the Russian centralized heating systems have a huge length. The technical condition of the heat networks in many settlements is unsatisfactory due to physical wear, lack of required thermal insulation and waterproofing, violations of the hydraulic and thermal conditions of the network, and for other reasons. In addition, due to the constant increase in group heating service tariffs and a limited amount of fuel resources, the problem of energy conservation in the heat supply sector is of particular importance. A significant role in solving this problem is given to the thermal insulation of pipelines and industrial equipment as a factor contributing to fuel economy and providing the necessary temperature conditions in insulated systems and normal sanitary and hygienic labor conditions in industrial premises [7,8]. However, thermal insulation can fully perform its function only if it is correctly selected and calculated [9-16], based on the requirements imposed on it by the production process [7,8,12,16].

2. Calculation methodology
The thermal resistance against an uninsulated pipe heat transfer, \( R_L \), is determined by the formula [10,11,14]:
\[ R_L = \frac{1}{\alpha_1 \pi d_1} + \frac{1}{2 \pi \lambda_1} \ln \frac{d_2}{d_1} + \frac{1}{\alpha_2 \pi d_2}, \]

where \( \alpha_1 \) is the coefficient of heat transfer from the 1st medium to the inner surface of the pipe wall, \( W/(m^2\cdot°C) \);
\( \alpha_2 \) is the coefficient of heat transfer from the pipe outer surface to the ambient air, \( W/(m^2\cdot°C) \);
\( \lambda_1 \) is the heat conductivity coefficient of the pipe material, \( W/(m\cdot°C) \);
\( d_1 \) and \( d_2 \) are inner and outer diameters of the pipe, relatively, \( m \).

The thermal heat transfer resistance \( R_{L_{\text{ins}}} \) of an insulated pipe is determined by the formula [10, 11, 14]:

\[ R_{L_{\text{ins}}} = \frac{1}{\alpha_{\text{ins}} d_1} + \frac{1}{2 \pi \lambda_{\text{ins}}} \ln \frac{d_{\text{ins}}}{d_1} + \frac{1}{\alpha_{\text{ins}} \pi d_{\text{ins}}}, \]

where \( \alpha_{\text{ins}} \) is the coefficient of heat-transfer from the insulation surface to the ambient air, \( W/(m^2\cdot°C) \);
\( d_{\text{ins}} \) is the outer diameter of the insulation, \( m \);
\( \lambda_{\text{ins}} \) is the heat conductivity coefficient of the thermal insulation, \( W/(m\cdot°C) \).

According to the literature analysis [9, 11, 12, 16], at a certain value of the outer diameter of the insulation, called critical, the thermal resistance of the insulation jacket is minimal. This value of the critical diameter, \( d_{cr} \), determined from the condition \( \frac{dR_L}{dd_{\text{ins}}} = 0 \), can be found by the formula:

\[ d_{cr} = \frac{2 \lambda_{\text{ins}}}{\alpha_{\text{ins}}}. \]

The dependence at \( \lambda_{\text{ins}} = \text{const} \), \( \alpha_{\text{ins}} = \text{const} \) is shown in figure 1.

![Figure 1. Dependence of the insulation jacket thermal resistance on the insulation outer diameter.](image)

With the values of the insulation diameter \( d_{cr} < d_{\text{cr}} \), an increase in the thickness of the thermal insulation from \( d_2 \) to \( d_{\text{cr}} \) gives a negative effect, since in this case the heat loss increases. Thus, the application of thermal insulation does not always lead to a reduction in heat losses by the pipeline.
When \( d_2 > d_1 \), the heat transfer resistance increases and only at a certain value of \( d_2 \) it becomes equal to the heat transfer resistance of the uninsulated pipe.

Let us find out at what external diameter \( d_4 \) of the ineffective insulation the heat transfer resistance (taking into account this insulation thickness) will again reach the same value as that of the uninsulated pipe \( R_L \). This condition will determine the ineffective thickness of the ineffective thermal insulation.

It follows from the condition of the above problem that the heat transfer resistances \( R_{ins}^L \) and \( R_L \) for the insulated and uninsulated pipes must be equal:

\[
\frac{1}{\alpha d_1} + \frac{1}{\alpha \lambda} \ln \frac{d_2}{d_1} + \frac{1}{\alpha \lambda_{ins}} \ln \frac{d_4}{d_2} + \frac{1}{\alpha d_1} = \frac{1}{\alpha \lambda} + \frac{1}{\alpha \lambda_{ins}} \ln \frac{d_2}{d_1} + \frac{1}{\alpha \lambda} \frac{d_4}{d_2} \tag{4};
\]

\[
\frac{1}{2\alpha \lambda_{ins}} \ln \frac{d_4}{d_2} + \frac{1}{\alpha \lambda_{ins}} \frac{d_4}{d_2} - \frac{1}{\alpha \lambda} \frac{d_4}{d_2} = 0 \tag{5}.
\]

An analytical solution to this problem is impossible. It is necessary to use numerical methods, for example, Newton's method [17-19]. With the correct choice of the initial approximation, this method will lead to reliable results.

According to figure 1, we can recommend to use the following value as an initial approximation:

\[
d_{s0} = d_2 + 2 \left( \frac{2\lambda_{ins}}{d_{ins}} - d_2 \right) \tag{6}.
\]

To solve the problem, we used the MATLAB R 2018b program designed to perform a wide range of mathematical problems [20].

Consider a steel pipe with an outer diameter of 45 mm, thermally insulated with foam-chamotte material [10]. To find the heat conductivity coefficient, we use the dependence for the selected type of insulation [10]:

\[
\lambda_{ins} = 0.28 + 0.00023 t_{amb}. \tag{7}
\]

We take the ambient air temperature \( t_{amb} = 0°C \) and heat carrier temperature \( t_m = 100°C \), then the average temperature of the insulation layer \( t_{ins} = 60°C \) [10]. Substituting the obtained temperature in this dependence, we get \( \lambda_{ins} = 0.2938 \text{ W/(m·°C)} \).

To find the heat-transfer coefficient of the heat-insulated pipeline surface, we use the following formula [11-13]:

\[
\alpha_{ins} = 11.6 + 7\sqrt{\omega}, \tag{8}
\]

where \( \omega \) is the air velocity, m/s.

Let the air velocity be \( \omega = 0 \text{ m/s} \) under the given conditions, then the heat-transfer coefficient of the insulation \( \alpha_{ins} = 11.6 \text{ W/(m}^2\cdot°\text{C)} \).

We take the coefficient of heat transfer from the pipe outer surface to the ambient air \( \alpha_2 = 10 \text{ W/(m}^2\cdot°\text{C)} \), which corresponds to horizontal pipelines with a high-emissivity coating.

Depending on the main parameters of the heat carrier and the diameter of the pipe, we obtain the diameter values of the foam-chamotte ineffective insulation. The calculation results are presented in table 1.

The calculation results presented in the table 1 show that if foam-chamotte material is used as thermal insulation, ineffective insulation diameters have values applicable in construction. That is, when applying foam-chamotte insulation of such a thickness, the heat losses of the heat pipeline will not decrease.
Table 1. Diameters of ineffective insulation for various parameters of the heat carrier and the pipe diameter.

| No. | Heat-carrier temperature (t_{bc}, °C) | Average temperature of insulation layer (t_{av}, °C) | Heat-conductivity coefficient of the insulation (\lambda_{ins}, W/(m·°C)) | Pipe outer diameter (d_2, m) | Approximate diameter of ineffective insulation (d_{x0}, m) | Outer diameter of ineffective insulation (d_x, m) |
|-----|-------------------------------------|-----------------------------------------------|---------------------------------|----------------------------|---------------------------------|---------------------------------|
| I   | 100                                 | 60                                           | 0.2938                          | 0.045                      | 0.0563                          | 0.1                             |
| II  | 100                                 | 60                                           | 0.2983                          | 0.038                      | 0.0633                          | 0.115                           |
| III | 150                                 | 80                                           | 0.2984                          | 0.045                      | 0.0579                          | 0.103                           |
| IV  | 150                                 | 80                                           | 0.2984                          | 0.038                      | 0.0649                          | 0.118                           |

Besides that, calculations were carried out for such types of insulation as mineral wool wired mats and pierced and foam-concrete products. The obtained data showed that applying a layer of any thickness from the above types of thermal leads to a reduction in heat loss.

3. Results

The results of the study indicate that, before applying thermal insulation to heat pipes, in addition to its main properties (heat conductivity, \lambda_{ins}, heat transfer coefficient from the insulation surface to the ambient air, \alpha_{ins}, temperature restriction, etc.), it is necessary to take into account the diameter of the inefficient insulation. With a diameter of ineffective insulation, the value of thermal resistance to heat transfer reaches the same value as without thermal insulation, that is, with a certain thickness of thermal insulation applied to a certain diameter of the pipeline, the same heat losses take place as in the absence of insulation.

4. Conclusion

In this paper, we conducted a study to determine the thickness of inefficient thermal insulation for materials currently used for heat pipelines. We used the MATLAB R 2018b environment to perform the calculations and analyzed the data obtained. The values of ineffective insulation diameter for some thermal insulating materials used in construction for a long time are as applicable to the pipeline insulation. That is, when applying such thermal insulation of the above thickness, heat losses of the pipelines do not decrease. Modern thermal insulating materials have very low values of ineffective insulation diameters that are not actually applicable in construction, at which there are the same heat losses as in the absence of thermal insulation. When reconstructing heat pipelines, special attention should be paid to the network segments with outdated thermal insulation materials. In these segments, it is important to avoid reaching an ineffective diameter, which implies an increase in heat losses.

References

[1] Starkova L G, Doroshenko E K and Khudyakova M A 2018 Assessment of the efficiency of using heat recovery units in ventilation systems in the conditions of the southern Urals IOP Conference Series: Materials Science and Engineering 2018 012096

[2] Starkova L G and Farkhutdinova E R 2016 Increase of the efficiency of the system of cooling of data processing center servers Procedia Engineering 2, "2nd International Conference on Industrial Engineering, ICIE 2016" pp 2345–51

[3] Starkova L G, Tkalenko A N, Abdullin R V and Starkova D A 2017 Analysis of the efficiency of using plate heat exchangers in the conditions of the South Urals BST: Construction Machinery Bulletin 2017 11(999) 32–4
[4] Anisimova E 2017 Modeling of the Thermal Regime of the Building Procedia Engineering Elsevier Ltd publishing house 206 795–9 https://www.sciencedirect.com/science/article/pii/S187705817352384

[5] Anisimova E and Shcherbak A 2017 Analyzing the efficiency of introduction of the intermittent heating mode "IOP Conference Series: Materials Science and Engineering (MSE)" (Publishing house of IOP Publishing Ltd.), article number 012084, http://iopscience.iop.org/article/10.1088/1757-899X/262/1/012084

[6] Anisimova E Yu 2012 Energy efficiency of the thermal conditions of a building using an optimal intermittent heating mode Bulletin of the South Ural State University. Series: Construction and Architecture 38(297) 55–9

[7] 2012 SP 61.13330.2012 Thermal insulation of equipment and pipelines. Updated edition of SNiP 41-03-2003 (with change N 1) (Moscow) p 56

[8] 2012 SP 124.13330.2012 Updated edition of SNiP 41-02-2003 Heating network (Moscow) p 78

[9] Isachenko V P, Osiyeva V A and Sukomel A S 1975 Heat transfer: Ed. 3rd rev. and add. (Moscow: Energy) p 488

[10] Hijnyakov S V 1976 Practical calculations of thermal insulation: Ed. 3rd rev. (Moscow: Energy) p 200

[11] Sokolov E Ya 2001 Heating and heating networks: Ed. 7th stereotypical (Moscow: Publishing house MEI) p 472

[12] Popyrin L S, Svetlov K S, Belyaeva G M et al (eds) 1989 Research of heat supply systems (Moscow: Science) p 215

[13] Dul'nev G N 2012 Theory of heat and mass transfer (SPb: NIU ITMO) p 195

[14] Kopko V M 2002 Thermal insulation of pipelines of heating systems (Minsk: Tehnoprint) p 160

[15] Sotnikova O A and Mel'kumov V N 2009 Heat supply (Moscow: Publishing House Association of Construction Universities) p 296

[16] Monahov G V and Voitinskaya Yu A 1995 Modeling control of heating network modes (Moscow: Energoatomizdat) p 224

[17] Amosov A A 1994 Computational Methods for Engineers: Study Guide (Moscow: Vyssh. shk.) p 544

[18] Patankar S V 2003 Numerical solution of the problems of heat conduction and convective heat transfer during flow in channels Per. from English Kalabina E V, ed Yan'kova G G (Moscow: Publishing house MEI) p 312

[19] Kuznecov G V and Sheremet M A 2007 Difference methods for solving heat conduction problems eds Kuznecov G V and Sheremet M A (Tomsk: Publishing house TPU) p 172

[20] Polovko A M and Butusov P N 2005 MATLAB for student (Spb.: BHV-Peturburg) p 320

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