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DETERMINATION OF HEAT ENERGY LOSSES BY UNDERGROUND HEAT PIPELINES TAKING INTO ACCOUNT SOIL MOISTURE

ВИЗНАЧЕННЯ ВТРАТ ТЕПЛОВОЇ ЕНЕРГІЇ ПІДЗЕМНИМИ ТЕПЛОВИМИ МЕРЕЖАМИ З УРАХУВАННЯМ ВОЛОГОСТІ ГРУНТУ

Vashchyshak I. R. / Ващишак І.Р.
c.t.s., as.prof. / к.т.н., доц.
ORCID: 0000-0002-9078-6726
Tsykh V.S. / Цих В.С.
c.t.s., as.prof. / к.т.н., доц.
ORCID: 0000-0002-9095-4099
Ivano-Frankivsk National Technical University of Oil and Gas
Івано-Франківський національний технічний університет нафти і газу

Abstract. *The relevance of the energy efficiency study for heat networks of heat supply enterprises in order to identify excess heat energy losses and determine their level is considered. The calculation method of normative heat losses in the heat pipeline is analyzed in accordance with the requirements of normative documents. It has been established that for an objective assessment of the heat pipelines' energy efficiency, the widespread introduction of heat energy metering devices and the improvement and updating of the methodological base for determining heat losses in underground heat pipelines based on the indicators of heat energy metering devices, installed on heat networks and at heat consumers, are required. The classification of the moisture regime of heat pipelines' thermal insulation is given for each type of laying: trench pipe laying, underground laying. On the basis of a comparative analysis of the specific heat loss calculation in the section of the underground heat pipeline, a significant influence of soil moisture on the deviation of the actual losses from the normative ones is shown. The method of thermal energy losses calculating for underground heating pipelines by taking into account the influence of soil moisture has been improved. The final analytical dependences for determining heat losses, taking into account the moisture regime of the heat pipe route, are given. This makes it possible to realize the general saving of energy resources, the ability to determine the energy efficiency of the heat supply system, forecast the consumption of fuel and energy resources in the future, and, most importantly, minimize the loss of energy resources during the transfer of thermal energy to the final consumer.*

Key words: *Energy control, energy loses, heat pipes, humidity*

Formulation of the general problem.

The main purpose of the heat supply system is to provide consumers with the required amount of heat with appropriate quality. The quality of thermal energy is determined by its temperature level, which is specified by the temperature schedule.

The analysis of the heat networks state, which are the part of the city's heat supply enterprises shows that there are excessive losses of thermal energy caused by the excessive service life of the pipelines, as well as the conditions of the pipelines and the lack of constant monitoring of their technical condition [1]. It has been established that modern approaches to determining the energy efficiency of underground heat pipelines should be directed to the development of a methodology for calculating normative heat energy losses in accordance with the requirements of regulatory documents, taking into account the conditions of pipelines and the influence of external factors.

Since the compensation of thermal energy losses during the transportation of the coolant is carried out by including such a cost in the bills for payment by end consumers, the accuracy of their calculation is a rather urgent task.

The state of its solution.

The calculation of normative losses of thermal energy in pipelines is carried out according to the requirements of KTM 204 Ukraine 244-94 [2] separately for thermal networks connected to each heat-generating source for the reporting period. The calculation is performed separately for pipelines of each diameter and type of laying.

Actual heat losses in heat networks depend on their length and diameters, laying method, type and condition of thermal insulation, soil conditions, service life, operating conditions, etc., and are determined on the basis of appropriate tests of technically sound pipelines.

Heat losses in heat pipelines are defined as the sum of heat losses with water leakage from pipelines and heat losses due to water cooling in pipelines [2].

Statement of the research problem.

In order to objectively assess the energy efficiency of heat pipelines of centralized heat supply systems, it is necessary to research the method of determining heat losses in heat networks and to develop a number of measures to reduce the level of excess heat energy losses.

Characteristics of the performed studies and kept results.

The calculation of thermal energy losses values for heating buildings in the heat supply system is carried out on the basis of the methods outlined in DBN V.2.5-39:2008 "Engineering equipment of buildings and structures. External networks and structures. Thermal networks", NPAOP 0.00-1.81-18 "Labor safety rules during operation of pressure equipment", DSTU-NB V.2.5-35:2007 "Engineering equipment of buildings and structures. External networks and structures. Heating networks and hot water supply networks using pre-insulated pipelines".

The input data for the calculation are the values of the thermal characteristics obtained during the instrumental measurement, in particular, the values averaged based on the results of several measurements of the coolant temperatures at the beginning and at the end of the supply and return pipelines, the values of the coolant consumption in individual sections, as well as data on the geometric parameters of the heat pipelines.

The calculation of heat losses by heat pipelines does not take into account the moistening of the thermal insulation of pipelines, which occurs due to the sorption of moisture from the soil due to the penetration of water through the broken protective covering layer in flooded channels. This is especially relevant for ductless laying, when the insulation layer is in contact with a layer of moist soil.

It should be noted that the presence of waterproofing with ductless laying has a positive effect only if it is airtight. In the case of air tightness violations, there is a possibility of wetting of the thermal insulation. Moreover, even small holes in the covering layer are enough to cause intense wetting of the thermal insulation in case of the channel flooding or rise of ground water in the case of channelless laying. Further drying of the thermal insulation is complicated precisely by the presence of a waterproofing layer, which prevents the escape of steam from the insulation to the outside, and thereby significantly worsens the conditions for drying the insulation. In these conditions, the waterproofing layer becomes a barrier to the exit of moisture and the drying process is delayed, many times exceeding the duration of the wetting process. Unfortunately, in most situations, there is no ideal, absolutely airtight layer, and in underground laying there is always the possibility of wetting the insulation due to the rise of groundwater or flooding of the pipeline with domestic sewage. At the same time, the drainage system must work properly to remove moisture from the canal, which is not always the case. At the same time, it is not even assumed that the covering layer should perform waterproofing functions.

On the basis of literary data, it is possible to note the most important moments of the moisture regime of pipelines' thermal insulation of heat networks for each type of laying.

Canal pipe laying.

In the heat losses calculations for the canal pipe laying, the air temperature in the channel is assumed, in most cases, to be equal to the temperature of the soil, i.e. in the range from -5 to +10 °C. At such temperatures, the air humidity in the channel is approximately close to 100%, which leads to abundant condensation on the bottom, walls and covering of the channel. The channel coating, as a rule, has the lowest temperature, since it is located closest to the surface of the earth. It is on it that condensation occurs, as a result of which water drops fall back onto the structure of the heat pipe and moisten it. At high relative humidity, faster aging of both the thermal insulation itself and the covering layer occurs. In addition, it should be noted that the covering layer in the channel lining does not perform a waterproofing function, but only keeps the main layer of thermal insulation from crumbling. It should be assumed that the covering layer is in normal condition and the humidity of the insulation depends only on the presence of water in the channel.

In urban conditions, underground pipelines are in different regimes, taking into account a large number of additional factors: the different state of their drainage system, the level of groundwater, the presence of industrial and domestic sewage, the state of drainage sewers, the presence of asphalt pavement. Therefore, in relation to channel laying, we will use the following distribution of channels according to their moisture status:

1. The canal is dry. For channel laying in the absence of water in the channel, the wetting of the thermal insulation is small. The average moisture content of materials can be accepted within 0.4% for mineral wool and 4% for foam plastics. It is not necessary to enter correction coefficients in this situation.

2. The canal is waterlogged. For channel laying, in the presence of water at the bottom of the channel, wetting of the thermal insulation takes place, but it will be moderate, since the wetting will occur only due to the sorption of moisture from the air and due to moisture flowing from the channel overlap. For mineral wool, the effect of capillary forces is small, so the excess moisture should flow to the lower part of the structure, which will not allow the entire insulation structure to get very wet. For fine-porous materials such as phenolic foam and polyurethane foam, the effect of capillary forces is much greater, and moisture will be retained. Therefore, in the absence of a hermetic covering layer, the humidity of such insulation will be much higher. The average values of moisture content of materials can be taken as follows: 5% for mineral wool, 15% for foam plastics and polyurethane foam.

3. The canal is totally flooded. This means that there is water at the bottom of the

channel, the level of which reaches, at least, the bottom of the pipeline structure, that is, it touches the thermal insulation. Wetting of thermal insulation is quite high. As mentioned above, the covering layer is not airtight, and it is not able to protect the insulation from getting wet under these conditions. Part or all of the insulation is in the mode of complete moisture saturation. When the pipeline is partially flooded, the moisture can be unevenly distributed along the height, so that the average moisture content of the insulation depends on the water level in the channel. The average humidity values of materials can be taken as follows: 20% for mineral wool, 80% for foam or polyurethane foam.

Trenchless pipe laying.

In the case of trenchless pipe laying, the temperature of the surface layer of insulation is equal to the temperature of the soil for the considered period, i.e. in the range from -5 to +10 °C. At high relative humidity, rapid aging of both the thermal insulation itself and the covering layer occurs. Insulation moisture mainly depends on soil moisture.

With a service life of up to a half of the standard service life, it is considered that the covering layer is in good working order and protects the insulation from excessive moisture. However, due to the fact that the pipeline is always in a humid environment, the humidity of the insulation is quite high even with a functional waterproofing layer. With low-moisture soils, taking into account the protective effect of the waterproofing layer, it is possible to take the value of insulation humidity at the level of 2%; with wet soil - 4%; with soil saturated with water - 25%.

In the event that the service life of the covering layer is more than a half of the normative one, it should be considered that the covering layer has partially collapsed and no longer fully fulfills its waterproofing properties. With low moisture soils, the moisture content of thermal insulation for ductless laying, taking into account the protective effect of the waterproofing layer, can be about 3%; with wet soil - 6%; with soil saturated with water - 40%.

If the service life of the covering layer exceeds the normative one, it should be assumed that the covering layer has completely collapsed and absolutely does not fulfill its waterproofing properties. With low-moisture soils, the moisture content of thermal insulation is about 6%; with wet soil - 13%; with soil saturated with water - 80%.

Thus, this suggests that to ensure the accuracy of the heat loss calculation through the insulation, it is necessary to use the thermal conductivity coefficients of the insulation, adjusted for humidity. This is especially important when laying pipelines directly into the soil.

According to [2], heat losses are calculated by the formula:

$$q = \frac{(t_W - t_A)}{\frac{1}{2 \cdot \pi \cdot \lambda_I} \cdot \ln\left(\frac{d_{II}}{d_{OI}}\right) + \frac{1}{\alpha_{OI} \cdot \pi \cdot d_{OI}}} = \frac{(t_W - t_A)}{R_I + R_{OUT}} \tag{1}$$

where t_W – water temperature in the pipeline, °C; t_A – ambient temperature, °C; λ_I – thermal insulation heat conductance, W/(m·°C); d_{II}, d_{OI} – inner and outer diameters of the insulation, respectively, m; α_{OI} – coefficient of heat transfer on the outer surface of thermal insulation, W/(m²°C); R_I – thermal resistance of the thermal insulation layer, (m·°C)/W; R_{OUT} – thermal resistance of the environment, (m·°C)/W.

Heat transfer from the heat carrier to the inner surface of the pipeline is not taken into account due to the fact that the coefficient of heat transfer from the heat carrier to the pipes inner wall is much higher than the heat transfer coefficient from the insulation's outer surface to the surrounding soil. The thermal resistance of the pipeline wall and the thermal resistance of the waterproofing can also be neglected, given the high thermal conductivity of the wall and its small thickness.

For underground canal pipe laying, dependence (1) is acceptable for calculation. However, with trenchless pipe laying, the heat from the surface of the protective layer is transferred directly to the soil, e.i. $R_{OUT} = R_S$. The value R_S is determined by the well-known formula of Forchheimer [3]:

$$R_S = \frac{1}{2 \cdot \pi \cdot \lambda_S} \cdot \ln\left[\frac{2 \cdot h}{d_{OI}} + \sqrt{\left(\frac{2 \cdot h}{d_{OI}}\right)^2 - 1}\right] \quad (2)$$

where λ_S – soil heat conductance, W/(m·°C); h – the depth of the pipelines axes, m.

Soil heat conductance λ_S depends on its structure and humidity, the value varies within quite wide limits: from 1 for sands to 3 for clay soils in a saturated state of moisture.

For a two-pipe trenchless pipe laying, the conditional thermal resistance of the soil should also be taken into account, which includes the decrease in heat transfer from the pipelines due to stronger heating of the soil layer between the pipelines. This resistance is determined by the formula:

$$R_{ADD} = \frac{1}{2 \cdot \pi \cdot \lambda_S} \cdot \ln\sqrt{1 + \left(\frac{2 \cdot h}{b}\right)^2} \quad (3)$$

where b – horizontal distance between pipe axes, m.

Thus, the formula for calculating thermal energy losses will take the form:

$$q = \frac{(t_W - t_A)}{\frac{1}{2 \cdot \pi \cdot \lambda_I} \cdot \ln\left(\frac{d_{OI}}{d_{II}}\right) + \frac{1}{2 \cdot \pi \cdot \lambda_S} \cdot \left[\ln\left[\frac{2 \cdot h}{d_{OI}} + \sqrt{\left(\frac{2 \cdot h}{d_{OI}}\right)^2 - 1}\right] + \ln\sqrt{1 + \left(\frac{2 \cdot h}{b}\right)^2}\right]} \quad (4)$$

Let's analyze the change in heat losses at different soil moisture levels. For ease of analysis, all graphs will be constructed for one underground section of the heat network laid in a ductless method: pipe diameter - 0.1 m; depth of occurrence - 1.5 m; the thickness of the waterproofing is 0.005 m, the distance between the axes is 0.7 m. The outside air temperature is 1 °C, the temperatures in the supply and return pipelines are 95 °C and 45 °C, respectively.

The thermal conductivity of insulation materials and soil at different humidity levels is taken from reference books and is given in the table 1.

In fig. 1 it is shown the influence of changes in soil moisture for polyurethane foam insulation of pipelines of different thicknesses, and Fig. 2 – for polyurethane foam and mineral wool insulation with a thickness of 3 cm both.

Table 1 - Thermal conductivity of materials

Material	Thermal conductivity, W/(m·°C)
Mineral wool	0,052
Polyurethane foam	0,035
Dry soil	0,4
Soil, 8% water	1,12
Soil, 15% water	1,36
Soil, 20% water	1,63
Soil, 40% water	2,0

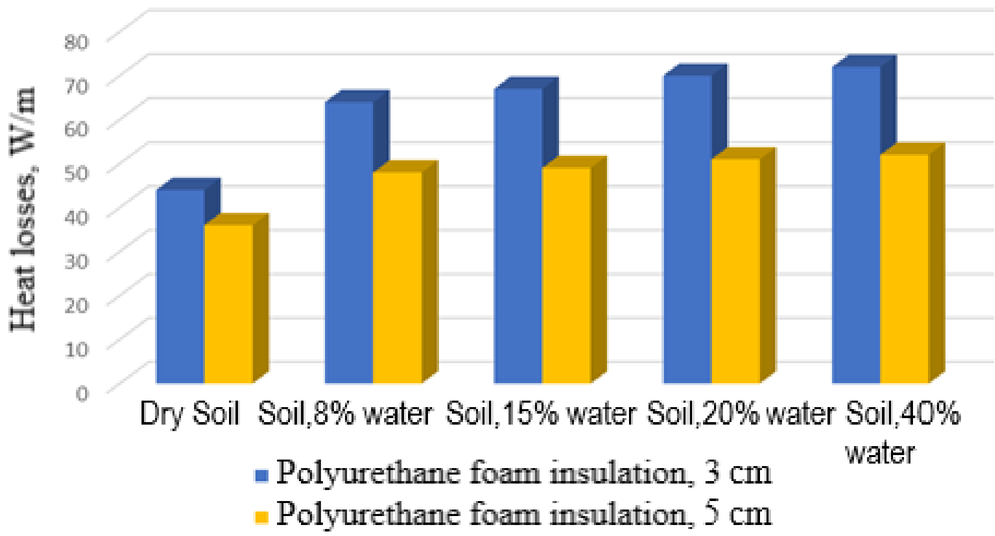

Figure 1 - The influence of soil moisture on specific heat losses for polyurethane foam insulation of pipelines

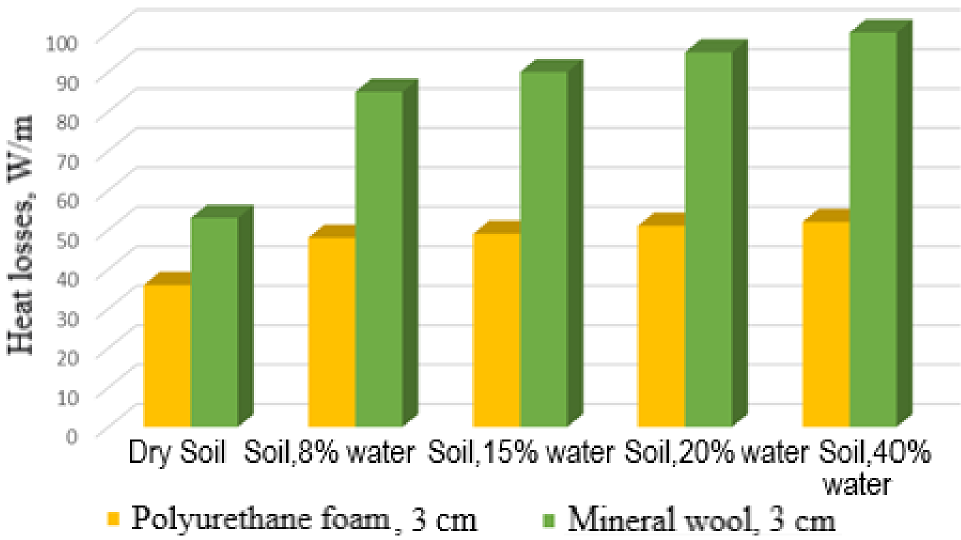

Figure 2 - The influence of soil moisture on specific heat losses with polyurethane foam and mineral wool insulation of pipelines of the same thickness

Specific heat losses with polyurethane foam and mineral wool insulation of pipelines with a thickness of 3 cm without taking into account the influence of soil moisture are: 55 W/m - for mineral wool insulation, 42 W/m - for foamed polyurethane insulation.

For the analyzed area, the specific heat loss with mineral wool insulation 3 cm thick is 53 W/m, while the value chosen from [2] is 55 W/m, which indicates that soil moisture is not taken into account. So, the soil is completely dry. When the soil is moistened up to 40%, the specific heat loss increases almost twice.

With foamed polyurethane insulation, the influence of soil moisture is much smaller: with dry soil, it is 44 W/m, and with moisture up to 40%, it is 72 W/m, that is, it increases more than 1.5 times.

When the thickness of foamed polyurethane insulation increases, the specific heat loss decreases, but the influence of soil moisture is monitored similarly. This indicates that the influence of soil moisture on specific heat losses cannot be eliminated by increasing the thickness of the insulating coating.

Thus, when calculating heat losses by underground heat pipelines, one cannot fail to take into account possible wetting of the insulating material due to soil moisture.

Conclusion.

A comparative analysis of the specific heat losses in the area of the underground heat pipeline calculation showed that the deviation of the actual losses from the normative ones may not always be caused by the unsatisfactory condition of the underground heat pipeline, but due to the significant influence of soil moisture.

Literature

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Анотація. *Розглянуто актуальність дослідження енергетичної ефективності теплових мереж теплопостачальних підприємств з метою виявлення понаднормативних втрат теплової енергії та визначення рівня втрат теплової енергії. Проаналізовано методику розрахунку нормативних втрат теплоти в теплових мережах відповідно до вимог нормативних документів. Встановлено, що для об'єктивної оцінки енергетичної ефективності теплових мереж централізованих систем теплопостачання потрібно повсюдне впровадження приладів обліку теплової енергії та вдосконалення і актуалізація методичної бази для визначення теплових втрат у підземних теплових мережах за показниками приладів обліку теплової енергії встановлених на теплових мережах і у теплових споживачів. Наведено класифікацію вологісного режиму теплової ізоляції трубопроводів теплових мереж для кожного виду прокладки: підземна канальна прокладка, підземна безканальна прокладка. На основі порівняльного аналізу розрахунку питомих теплових втрат* *на ділянці підземної теплової мережі показано значний вплив вологості ґрунту на відхилення фактичних втрат від нормативних. Удосконалено методику розрахунку втрат теплової енергії трубопроводами підземних теплових мереж шляхом урахування впливу вологості ґрунту. Наведено кінцеві аналітичні залежності для визначення втрат тепла з урахуванням вологісного режиму пролягання теплотраси. Це дає змогу здійснити загальну економію енергоресурсів, можливість визначити енергоефективність системи теплопостачання, спрогнозувати споживання паливно-енергетичних ресурсів в майбутньому, і, найголовніше, мінімізувати втрати енергоресурсу під час передачі теплової енергії кінцевому споживачу.*

Ключові слова: *Енергетичний контроль, втрати енергії, теплові мережі, вологість*