New approach to estimation of thermal conductivity coefficient for underground pipeline forming a thawing halo in permafrost

N A Garris, A I Rusakov¹ and L R Baykova²

Ufa State Petroleum Technological University, Pipeline Transport Department,
450062 Ufa, Russia

¹eldniwe@yandex.ru, ²hydrolyalya@mail.ru

Abstract. Practice of northern oil pipelines operation shows that operating modes of pipelines in permafrost are practically incomputable. The fact of surrounding soil thawing changes the conditions of heat transfer so drastically that conventional methods of non-isothermal pipelines calculation prove to be inapplicable both in the cases of thawing and freezing soils. Analysis of data obtained during the experimental study of physical model has shown that, depending on the phase state of soil moisture and the type of ice formation, thermal conductivity coefficient of frozen soil may exceed to twice the coefficient of thawed soil. The proposed equation for soil thermal conductivity coefficient estimation makes it possible to determine the external heat transfer and to calculate the pipeline temperature profile according to conventional method of non-isothermal oil pipelines thermal calculation.

1. Introduction
The practice of northern oil pipelines operation shows that operating modes of pipelines in permafrost are practically incomputable. The fact of surrounding soil thawing changes the conditions of heat transfer so drastically that conventional methods of non-isothermal pipelines calculation prove to be inapplicable both in the cases of thawing and freezing soils [1].

Change of soil moisture phase state and, accordingly, thawing or freezing halo diameter, alters thermophysical properties of soil. The soil in the thermal influence zone becomes anisotropic and heterogeneous [2–4]. Climate factors also affects the heat exchange greatly, which can result in change of thawing zone shape; this is especially distinct in the summer, when the thawing area takes a trough shape.

Currently there is no consistent approach for calculating such a complex system as "non-isothermal pipeline – thawing frozen ground".

At present, numerical methods are widely used to solve practical problems, such as determination of thawing halo development around the pipeline in time. Despite some undeniable advantages, the complexity of setting boundary conditions, especially the wall temperature of the pipeline, makes it difficult to obtain a reliable solution even if there is an adequate calculation model. Despite the significant expenditure of labor and resources, the task of determining the temperature regime of the pipeline in frozen soils remains unresolved [5–7].

Despite the overall difficulty of problem formulation, it can be simplified by referring to the practical experience gained in studying the heat transfer of hot and non-isothermal main pipelines [8, 9].
2. Estimation of non-frozen soil thermal conductivity coefficient

As a result of the thermal impact of the pipeline on the surrounding soil, moisture migrates to the periphery under the influence of thermal forces within the zone of the pipeline thermal influence. With decreasing humidity, the thermal conductivity of the soil adjacent to pipeline also decreases [2, 10 - 15]. A typical pattern of variation of soil thermal conductivity coefficient $\lambda$ with increasing distance from the non-isothermal pipe with a diameter $D$ of 0.219 m ($r$ - distance from the pipe wall) is shown in Figure 1.

\begin{equation}
\lambda_s = \frac{\lambda_u \cdot \lambda_w}{\ln \frac{\lambda_u}{\lambda_w}} 
\end{equation}

where $\lambda_u$ and $\lambda_w$ are respectively the thermal conductivity coefficients of soil in the natural undisturbed thermal state at the depth of the pipeline axis laying and of soil adjacent to the pipeline wall, that is, at the temperature of the pipe wall.

The model was tested on wide range of hot [9-11] and others non-isothermal oil pipelines. Formula (1) was defined as the main for determining the calculated coefficient of soil thermal conductivity in the design of non-isothermal pipelines [16].

The extensive long-term practice and experience of operating existence non-isothermal pipelines have proved the validity of such an approach to solving the most complicated practical problems of heat exchange of pipelines with surrounding soil. The calculation of the temperature regime for oil pipelines can be performed using the Shukhov formula, and taking into account the Joule-Thomson effect for gas pipelines when laying in ordinary, i.e. non-frozen soils.

The calculation of the internal heat transfer of the pipeline is not difficult, since there are enough formulas for determining the internal heat transfer coefficient $\alpha_1$ for both oil pipelines and gas pipelines. The simplest formula for calculating the external heat transfer coefficient $\alpha_2$ of a small diameter pipe, with a relative laying depth $H/D > 2 ... 3$, is the Forchheimer formula (2)
\[ \alpha = \frac{\lambda_s}{D \cdot \ln 4H} \]  

(2)

where \( \lambda_s \) is the calculated coefficient of soil thermal conductivity, which is determined for ordinary soils by formula (1) on the basis of [1, 10].

The structure of the formula (2) for determining \( \alpha \) is also preserved in more complex representations of Forchheimer-Greber, Arons-Kutateladze, Tugunov-Yablonsky, and others, which take into account the resistance to heat transfer from the soil surface to the air and additional resistance of the snow cover. However, in any case, the external heat transfer directly depends on the coefficient of soil thermal conductivity \( \lambda_s \) [16].

Thus, the determination of the actual value of the coefficient of soil thermal conductivity is one of the most important issues in the pipelines design, since the heat loss from the pipeline to the environment, and, consequently, the capital and operating costs of transporting hydrocarbons, is practically proportional to the thermal conductivity coefficient \( \lambda_s \).

3. Justification of frozen soil thermal conductivity coefficient estimation

In frozen soils, under the pipeline thermal influence, redistribution of moisture and change in the ice content also occurs. But the problem seems more complicated, as a thawing halo is formed around the pipeline, and a separate zone in the altered, thawed state is formed in the array of the enclosing frozen soil. Ground, by definition, becomes heterogeneous. In addition, migration processes in capillaries of soil (which can be considered as a capillary-porous body) occur simultaneously with a change in the phase state of ground moisture [2].

According to the reference data [17, 18], the difference in the thermal conductivity coefficients of soil in thawed and frozen states is small, and for soils in natural, undisturbed state and at the same humidity, is in the ratio: \( \lambda_t = (1.05...1.3) \lambda_{th} \).

At the same time, it is well known that as a result of anthropogenic impact (pipeline laying), the thermophysical state of the soil is significantly disrupted along the entire exclusion zone [19-22]. The depths of seasonal thawing and freezing increase from 2 to 4 times. Changes in humidity, ice content and thermal conductivity are almost unpredictable. The choice of the estimated soil characteristics and the calculation of the pipeline temperature regime becomes problematic.

The thermal conductivity of the soil matrix, or dry soil, is slightly dependent on temperature, yet the moist soil shows very distinct properties when the temperature passes through the zero threshold in the range (0...-5 °C). This is explained by the fact that the thermal conductivity of wet soil as a media depends on the thermal conductivity of the individual components. Depending on the phase state of ground moisture (water, ice, steam-air fraction) and the type of ice formation, up to the formation of ice-cementation bonds in phase transitions, a thermal conductivity coefficient of frozen soil may exceed to twice the coefficient of thawed soil in the conditions of one-dimensional flows, as noted in [23].

This fact is confirmed by experiments carried out at the Ufa State Petroleum Technological University [24]. The experiment was conducted on a number of pipes with diameter range of 0.060...0.325 m, length of 5...13 m and 1.6 m depth of laying. The pipes were placed polar-parallel and had a net of thermocouples (100 pcs) in the middle section, covering the zone of 3x9 m. The experiment processing was based on Fourier law of thermal conductivity.

The constancy of the heat flux \( q \) was provided by electric heating with delicacy of \( \delta_q = \pm 2.5\% \). The areas of the isothermal surfaces and the values of the temperature gradients were determined as a result of graphical processing of the temperature fields by means of curvimeter. The limiting relative errors of determination, based on [24], are \( \delta_t = \pm 19.0\% \); \( \delta = \pm 2.0\% \).

Figure 2 shows the results of processing one of the experiments conducted to control thawing halos around the underground pipeline. Dependences of sandy soil thermal conductivity coefficient \( \lambda \) and humidity \( w \) from the pipeline axis distance \( r/R \) are typical for the case of heat exchange of an underground pipeline in permafrost. The thawed ground zone (\( t > 0 \) °C), the phase transitions zone (\( t = 0 \ldots -5 \) °C) and the frozen ground zone (\( t < -5 \) °C) are clearly distinguished.
The experiment shows that the pipeline as a source of heat creates a continuous spectrum of phase transition temperatures (thawing - freezing). This means that congelation of water, or ice melting, occurs along the thickness of frozen ground. With increase of distance from the pipeline, with drop in temperature and increase in ice content, thermal conductivity of soil increases.

![Figure 2](image-url)

**Figure 2.** Change in coefficient of thermal conductivity $\lambda$ and total humidity $w$ of sandy soil in the pipeline section area in the thawing regulation mode [24]

It was also found that the phase transitions zone (0...-5 °C) is always present, both during soil thawing and freezing. This is explained by the fact that capillary water freezes first in this temperature interval with decreasing temperature, and appearance and formation of ice crystals partly occurs due to film pellicular water, which the thermal conductivity exceeds that of gravity water four times. The more water is adhered to the ground, the more its thermal conductivity is [2, 23].

Table 1 shows the results of experiment carried out under physical modeling conditions for a period corresponding to the pipeline annual period of operation (at a relative laying depth of $H/R = 3.62$) in a controlled temperature regime.

The soil thermal conductivity coefficients were determined as average values based on temperature fields processing:

- $\lambda_{th}$ – thermal conductivity coefficient of thawed soil within the thawing halo of radius $R_0$;
- $\lambda_f$ – thermal conductivity coefficient of frozen soil, including the phase transitions zone;
- $\lambda_{exp}$ – thermal conductivity coefficient of the pipeline thermal influence zone, determined as a mean integrated value, obtained experimentally as a result of solving the reverse heat conduction problem.

The estimated value of the soil thermal conductivity coefficient $\lambda^*$, is defined as the mean integral value in the pipeline thermal influence zone and can be calculated by the formula (3), similar to (1):

$$\lambda^* = \frac{\lambda_f - \lambda_{th}}{\ln \frac{\lambda_f}{\lambda_{th}}}$$

(3)
Table 1. Change of heat transfer parameters of the pipeline model in permafrost\textsuperscript{a} [24]

| Month | $R_0/R$ | Thermal conductivity coefficients, W·(m·\degree C)$^{-1}$ | $\delta$, % |
|-------|---------|----------------------------------------------------------|----------|
| I     | 4.66    | $\lambda_0$ 1.041, $\lambda_d$ 1.823, $\lambda_{exp}$ 1.363, $\lambda_s^*$ 1.396 | 2.42     |
| II    | 3.14    | $\lambda_0$ 1.100, $\lambda_d$ 1.771, $\lambda_{exp}$ 1.483, $\lambda_s^*$ 1.409 | 4.99     |
| III   | 2.76    | $\lambda_0$ 1.035, $\lambda_d$ 1.381, $\lambda_{exp}$ 1.265, $\lambda_s^*$ 1.199 | 5.22     |
| VI    | 1.88    | $\lambda_0$ 0.894, $\lambda_d$ 1.576, $\lambda_{exp}$ 1.390, $\lambda_s^*$ 1.203 | 13.45    |
| V     | 1.40    | $\lambda_0$ 0.796, $\lambda_d$ 1.461, $\lambda_{exp}$ 1.279, $\lambda_s^*$ 1.077 | 15.87    |
| VI    | 1.65    | $\lambda_0$ 0.969, $\lambda_d$ 1.780, $\lambda_{exp}$ 1.509, $\lambda_s^*$ 1.334 | 11.60    |
| VII   | 1.50    | $\lambda_0$ 0.762, $\lambda_d$ 1.862, $\lambda_{exp}$ 1.496, $\lambda_s^*$ 1.390 | 7.09     |
| VIII  | 2.04    | $\lambda_0$ 0.965, $\lambda_d$ 3.279, $\lambda_{exp}$ 1.716, $\lambda_s^*$ 1.529 | 10.90    |
| IX    | 2.83    | $\lambda_0$ 1.047, $\lambda_d$ 2.639, $\lambda_{exp}$ 1.753, $\lambda_s^*$ 1.722 | 1.82     |
| X     | 3.43    | $\lambda_0$ 1.111, $\lambda_d$ 2.838, $\lambda_{exp}$ 1.769, $\lambda_s^*$ 1.842 | 4.13     |
| XI    | 4.13    | $\lambda_0$ 1.112, $\lambda_d$ 2.635, $\lambda_{exp}$ 1.716, $\lambda_s^*$ 1.765 | 2.83     |
| XII   | 3.75    | $\lambda_0$ 1.173, $\lambda_d$ 2.249, $\lambda_{exp}$ 1.797, $\lambda_s^*$ 1.163 | 8.01     |

Average values 1.0 2.108 1.545 1.419

\textsuperscript{a}The relative error of mean value $\lambda_s^*$ is $\delta_{avg}$ = 8.16%.

The limiting relative error of the calculated value of soil thermal conductivity coefficient $\lambda_s^*$, relative to the experimentally obtained value $\lambda_{exp}$ was determined with the formula (4):

$$
\delta = \frac{|\lambda_{exp} - \lambda_s^*|}{\lambda_{exp}}
$$

As it can be seen from the calculations, the greatest limiting relative error $\delta = 15.87\%$ is observed in the case of small thawed zone dimensions ($R_0/R = 1.4$) and predominance of frozen ground in the thermal influence zone.

The analysis of the obtained data made it possible to reveal the consequences of anthropogenic impact on frozen ground during pipeline laying. Disruption of cryogenic structure leads to a substantial change of soil thermal conductivity. The instability of heat exchange processes, which manifests itself in periodic thawing and subsequent freezing of the enclosing soil, leads to segregation processes that affect the default cycle of cryostructures formation.

As a result, the difference in the thermal conductivity of thawed and frozen ground in the pipeline thermal influence zone is considerably greater than in undisturbed state, and reaches $\lambda_d/\lambda_{th} = 2$, which is fully consistent with the results [23], obtained in the study of thermal conductivity of rocks.

The method of soil thermal conductivity coefficient estimation according to formula (2) makes it possible to simplify the calculation of the temperature regime of the underground pipeline forming thawing halo in frozen soils.

3.1. Example

For an underground pipeline with a diameter $D=0.426$ m and with a relative laying depth $H_0/D=1.2/0.426=2.82$ laid in soils with thermal conductivity coefficients of frozen soil $\lambda_f = 1.771$ W·(m·\degree C)$^{-1}$ and thawed soil $\lambda_{th} = 1.409$ W·(m·\degree C)$^{-1}$, the estimated value of thermal conductivity coefficient, determined by (2), is equal to

$$
\lambda_s^* = \frac{1.771 - 1.409}{\ln \frac{1.771}{1.409}} = 1.584 \text{ W} \cdot (\text{m} \cdot \text{\degree C})^{-1}
$$
For an uninsulated underground pipeline, the heat transfer coefficient \( k \) is practically proportional to
the external heat transfer coefficient \( \alpha \). Determining the external heat transfer by the Tugunov-
Yablonsky formula (5), we obtain:

\[
 k \approx \alpha_2 = \frac{2 \cdot \lambda_s}{D \left( \ln \frac{4 \cdot H}{D} + \frac{\lambda_s}{\alpha_{air} \cdot H} \right)} = \frac{2 \cdot 1.584}{0.426 \left( \ln \frac{4 \cdot 3.463}{0.426} + \frac{1.584}{15 \cdot 3.463} \right)} = 2.117
\]  

(5)

where the heat-insulating effect of compressed snow cover with thickness \( H_{snow} = 0.5 \text{ m} \), with a thermal
conductivity coefficient \( \lambda_{snow} = 0.35 \text{ W} / (\text{m} \cdot \text{°C}) \), and heat transfer coefficient from snow surface to air is
\( \alpha_{air} = 15 \text{ W} / (\text{m}^2 \cdot \text{°C}) \) is taken into account by the introduction of the Greber correction (6):

\[
 H = H_0 + H_{snow} \cdot \frac{\lambda_f}{\lambda_{snow}} = 1.2 + 0.5 \cdot \frac{1.584}{0.35} = 3.463 \text{ m}
\]  

(6)

During soil congelation, thermal conductivity increases \( (\lambda_f = 1.771 \text{ W} / (\text{m} \cdot \text{°C})) \), heat transfer
coefficient increases accordingly and becomes \( k \approx \alpha_2 = 2.318 \text{ W} / (\text{m}^2 \cdot \text{°C}) \). The difference in total heat
transfer coefficient determination in this example is 9.5%.

Consequently it is necessary to take into account ground moisture phase state in calculation of an oil
pipeline operating regimes in permafrost conditions, which can be done with the help of formula (3).

4. Results

1. Calculation of temperature regime of the underground pipeline forming thawing halo in frozen soils
can be simplified by determining the estimated value of soil thermal conductivity coefficient in the
pipeline thermal influence zone as a mean integral value.

2. It has been experimentally proved that the difference in soil thermal conductivity coefficients in
thawed and frozen conditions in pipeline thermal influence zone can be substantially greater than
observed under natural conditions as a result of anthropogenic impact on the soil. The ratio of thermal
conductivity coefficients can reach \( \lambda_f / \lambda_0 = 2 \).

References

[1] Tugunov P 1984 Non-stationary modes of oil and oil products transfer (Moscow: Nedra
Publishing)

[2] Feldman G1988 Migration of moisture in melted and freezing ground (Novosibirsk, Nauka
Publishing)

[3] Bonacina C, Gomini G, Fasano A, Primicerio M 1973 Numerical solution of phase-change
problems Heat Mass Transfer 16 1825–32

[4] Farouki O 1981 The thermal properties of soils in cold regions Cold Regions Science 5 67–75

[5] Zotov M, Ushakov I, Dimov I and Oleinikova A 2012 Application of software solutions to
calculate stress-strain behaviour of pipelines laid on permafrost soils OOPPT: Science &
Technologies 1 61–5

[6] Yu W, Liu W, Lai Y, Chen L and Yi X 2014 Nonlinear analysis of coupled temperature-seepage
problem of warm oil pipe in permafrost regions of Northeast China Applied Thermal
Engineering 70 988–95

[7] Lu T and Wang K 2008 Numerical analysis of the heat transfer associated with
freezing/solidifying phase changes for a pipeline filled with crude oil in soil saturated with
water during pipeline shutdown in winter Journal of Petroleum Science and Engineering 62
52–8

[8] Arons A and Kutateladze S 1936 Heat transfer from non-insulated pipes to the ground in a non-
stationary state Proc. of the Scientific and Production Association for Research and Design of
Power Equipment. Problems of Heat Supply 11 34–7

[9] Galiev V, Tugunov P and Garris N 1981 Features of calculation and design of pipelines for
viscoplastic fluids transportation with heat of friction Oil and Gas 2 72–6
[10] Garris N, Tugunov P and Galiev V 1979 Determination of start-up pressure and pump supply while resuming hot pumping *Oil Industry* **8** 48–50
[11] Garris N and Novoselov V 1986 Determination of soil thermal conductivity coefficient by its mechanical composition *Oil Industry* **3** 51–2
[12] Haigh S 2012 Thermal conductivity of sands *Gêotechnique* **62-7** 617–25
[13] Jin H, Wang Y, Zheng Q, Liu H and Chadwick E 2017 Experimental study and modelling of the thermal conductivity of sandy soils of different porosities and water contents *Applied Science* **7-119** 17
[14] Chen Sh 2008 Thermal conductivity of sands *Heat Mass Transfer* **44** 1241–6
[15] Tian Z, Lu Y, Horton R and Ren T 2016 A simplified de Vries-based model to estimate thermal conductivity of unfrozen and frozen soil *European Journal of Soil Science* **67** 564–72
[16] Agapkin V, Krivoshein B and Yufin V 1981 *Thermal and hydraulic calculations of pipelines for oil and oil products* (Moscow: Nedra Publishing)
[17] Velli Yu, Dokuchaev V 1977 *Reference book on construction on permafrost soils* (Saint–Petersburg: Stroiizdat Publishing)
[18] SP 25.13330.2012. *Rafts and foundations on permafrost. Revised edition SNiP 2.02.04-88 (Construction norms & regulations)* (Moscow: Regional development ministry of Russian Federation Publishing)
[19] Gambino G and Harrison J 2017 Rock engineering design in frozen and thawing rock: current approaches and future directions *Procedia Engineering* **191** 656–65
[20] Doré G, Niu F and Brooks H 2016 Adaptation methods for transportation infrastructure built on degrading permafrost *Permafrost and Periglac. Proc.* **27** 352–64
[21] You Ya, Yu Q, Guo L, Wang X, Hu J, Qian J and Zhang H 2016 In-situ monitoring the thermal regime of foundation backfill of a power transmission line tower in permafrost regions on the Qinghai–Tibet Plateau *Applied Thermal Engineering* **98** 271–9
[22] Wang T, Zhou G, Wang J and Zhao X 2016 Stochastic analysis of uncertain thermal characteristic of foundation soils surrounding the crude oil pipeline in permafrost regions *Applied Thermal Engineering* **99** 591–8
[23] Ershov E 1974 *Thermophysical properties of rocks* (Moscow: MGU Publishing)
[24] Garris N 1998 Operating of oil-products pipelines in different charging and temperature conditions considering requirements of environmental integrity *Dr. of tech. sci. diss.*