Journal of Engineering Science and Technology
Vol. 16, No. 1 (2021) 543 - 555

ANALYTICAL SOLUTION OF THE PROBLEM OF HEAT EXCHANGE OF BURIED PIPELINE WITH ATMOSPHERE IN THE CONDITIONS OF SNOW COVER

EVGENIY V. MARKOV*, SERGEY A. PULNIKOV,
YURI S. SYSOEV, D. V. RACHKOV, E. P. BRAGAR

[1]Industrial University of Tyumen, 38, Volodarskogo, 625000, Tyumen, Russian Federation
*Corresponding Author: markov.ev@mail.ru

Abstract

Pipeline transport of oil, gas and gas condensate in the cold regions is associated with the crossing of permafrost. The thermal influence of the pipeline produces freezing-thawing processes in permafrost and strong bending of the pipeline. Therefore, the calculation of the temperature mode of the pipeline remains an urgent task. Climatic conditions in cold regions are characterized by snow cover with low thermal conductivity. Recent studies have shown that snow cover can significantly affect the cooling rate of pipelines in cold regions. Unfortunately, predicting the temperature mode of pipelines longer than 100 km using 3D finite element modeling requires significant computation power. Therefore, the purpose of this work is to get an analytical formula for heat flux from pipeline to the atmosphere in the presence of snow cover. The authors used 2D finite element modeling to get numerical values of the dimensionless heat transfer coefficients and approximated these values using analytical formula. The new formula as compared to the existing one shows the heat transfer coefficients by 10-14% less for the pipelines with diameters 1.42m, 0.72m, and 0.32m. The authors note that the purpose of this work is not to validate the formula on an operating pipeline. Therefore, the authors recommend using the new formula with caution and only for the coinciding boundary conditions, Nusselt number from 0.0005 to 100, the dimensionless depth of laying from 1.05 to 100.

Keywords: Cold regions, Heat transfer coefficient, Permafrost, Temperature mode of the buried pipeline.

1. Introduction

Considerable volume of hydrocarbon resources in the world is transported in the conditions of permafrost and high snow cover. These are the northern territories of Russia, China, Canada and the USA (Alaska). The product in a pipeline (oil, natural gas or natural gas liquids) usually has a temperature higher than the temperature of frozen soil. Thermal influence leads to thawing of ice lenses, subsidence of the soil, and bending of a pipeline.

Bronfenbrener and Korin [1] and Lisin et al. [2] showed the reducing of pipeline cooling rate in case of high snow cover with low thermal conductivity. As a result, the product temperature remains at the level of 10-30 °C throughout the pipeline route. Li et al. [3] and Wang et al. [4, 5] studied the influence of hot China - Russia crude oil pipeline to the permafrost. Thawing of permafrost has led to pipeline subsidence of more than 1.5 m since 2011. Dwight et al. [6] performed a similar study on the trans-Alaska pipeline and found significant permafrost thawing. Nikolaeva et al. [7] showed that such large subsidence of the soil leads to dangerous bends in the pipeline. Thus, the calculation of the temperature mode of the pipeline in permafrost must be performed with maximum accuracy.

However, the temperature of the product influences not only peermafrost, but also the pipeline itself. Liang et al. [8], Wang et al. [9] and Lazarev et al. [10] showed the temperature stresses lead to vertical buckling and lateral buckling. Fedorov et al. [11] showed that gas temperature significantly influences to the fragility of reinforced polyethylene pipes (RPP) after continuous operation. Bondarev et al. [12] showed the influence of temperature on the possibility of hydrates formation and narrowing the cross section of the pipe. Sunagatullin et al. [13] showed that product temperature significantly influences hydraulic losses in oil pipelines. Li et al. [14] and Markov et al. [15, 16] investigated the hydro-thermal interaction of the pipeline with the environment and found a significant redistribution of moisture, which can lead to frost heaving and deformation of the pipeline. Thus, the calculation of heat losses from the pipeline to the atmosphere is also important from the point of view of steel wear rate and pipeline throughput.

The first formula for calculating the heat flux from the pipeline to the atmosphere was deduced by Forchheimer. This formula represents an analytical solution of the heat equation using the line heat source method. One source and one drain of equal power are placed at the same distance from the soil surface. In this case, the surface temperature at each point is equal to a constant. The thermal resistance of the snow cover is not taken into account in the final formula [17].

Then Arons and Kutateladze improved the Forchheimer formula by including a term for the thermal resistance of the snow cover [18]. They introduced the concept of effective soil thickness, which is equal to the thickness of snow multiplied by the ratio of thermal conductivity of soil and snow. This article shows that Arons and Kutateladze approach gives an error 10-14% for some operated pipelines compared to the exact mathematical solution.

Unfortunately, the Arons and Kutateladze formula is the latest achievement in the field of the analytical solution of the problem of heat transfer from the pipeline to the atmosphere. Further research was aimed to improving the accuracy using numerical and empirical methods.

Improving the accuracy of calculations can be achieved by the semi-empirical method using direct measurements at an existing pipeline. Such methods were investigated by Garris et al. [19] and Polovnikov et al. [20]. The proposed methods adjust the initial data to better match the calculated and actual temperature fields.

However, the semi-empirical approach has a very limited scope. Empirical data are not available for design objects. Therefore, methods for numerical modeling of underground pipelines was developed together.

A key feature of the snow cover is a variable thickness, which can be zero in the warm season. In the warm season, the mesh of finite elements in snow cover domain should become infinitely thin in the vertical direction. This is a significant problem for most commercial programs. Therefore, practically the snow cover is described using convective heat transfer coefficient [21].

The widespread of the finite element method significantly increased the complexity of the solved problems. New mathematical models with higher accuracy have been developed for thermal problems. Korotkov et al. [22] developed a method for more accurately consideration of climatic condition using the measurements on the soil surface. Stepanov et al. [23] developed a method for more accurately accounting of radiation heat transfer on the surface of soil and snow. Zhang et al. [24] and He et al. [25] developed new mathematical models that take into account not only heat transfer, but also water-vapor-heat migration in soils and snow.

Kalyuzhnyy et al. [26] regarded the snow cover as a viscous body, which compacts under the influence of gravity. However, they consider the one-dimensional problem of heat and mass transfer in soils. Extending of these results for 2D space seems to be very difficult.

Probabilistic models deserve special attention. Gunar et al. [27] proposed a method for calculating the probability of a heat flux from a pipeline to the atmosphere. The initial data in their model is the probability density distribution of air temperature, snow cover thickness, wind speed, etc. Snow cover is described also using convective heat transfer coefficient.

Authors note that numerical simulation methods work well only in 2D problems. 3D coupled thermo-hydraulic calculation is extremely difficult for pipelines with the length of more than100 km. This is due to the number of finite elements and hardware requirements. Markov et al. [28] suggested a way to work around this problem using the set of 2D planes. However, in practice, software for solving this problem automatically is missing. Therefore, engineers are in the conditions when the mathematical base for the calculation exists, but there are no simple and convenient programs. In this case, the use of simple and convenient analytical formulas gives significant time savings.

Therefore, the purpose of this work is the improving of the analytical method for calculating the heat flux from the pipeline to the atmosphere. The authors decided to improve Arons and Kutateladze formula with the help of the exact solution of the problem of heat transfer from the pipeline to the atmosphere in the conditions of snow cover.

The authors of the article note that the purpose of the article is not to verify the new formula in the conditions of a physical experiment on an existing pipeline. However, the authors amend the existing formula in such a way that the heat flux corresponds to the exact solution of heat conduction problem in a solid with an error of less than 1.5%. Therefore, the authors consider this formula is more accurate than the existing Arons and Kutateladze formula.

2. Problem Statement

In the article the authors solved the following problems:

1) Developing a mathematical model and calculation scheme for determining the heat flux from the pipeline to the atmosphere through the soil and snow cover. Transforming the problem to the dimensionless form.
2) Estimating the convergence of the numerical method. Determining the sizes of the computational domain, providing a calculation error of less than 1%.
3) Performing a multivariate numerical study for determining the dimensionless heat transfer coefficient. Approximating the results of calculation by analytical formula with an error of not more than 1.5%.
4) Comparing the calculation results between existing and new formulas. Assessing the effect of snow cover on the heat flux from the pipeline to the atmosphere.

3. Underground Pipeline Mathematical Model and Calculation Scheme

Calculation scheme of heat exchange of an underground pipeline with atmosphere through the snow cover is shown in Fig. 1.

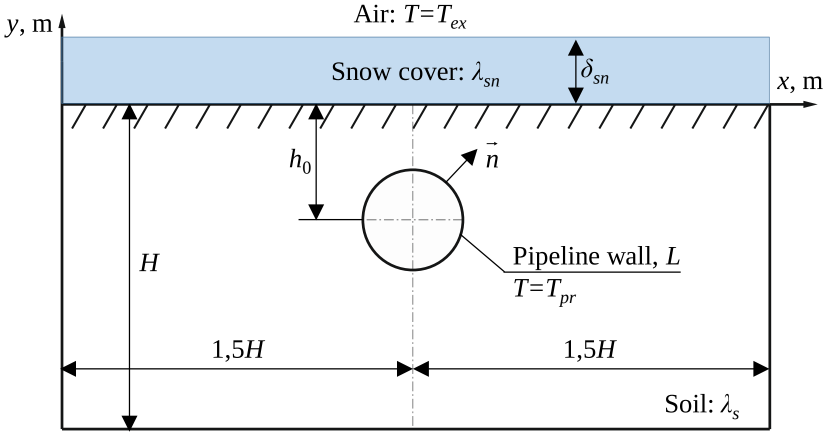

Fig. 1. The calculation scheme of heat exchange of underground pipeline with atmosphere through the snow cover.

The next assumptions are used in the calculating scheme:

1) The soil is homogeneous; the thermal properties are independent of temperature. This assumption is the same as in the Arons and Kutateladze formula [18].
2) Snow cover is described by the convective heat transfer coefficient. This is a classic decision for numerical models as in [21, 27, 28]:

$$\alpha = \lambda_{sn} / \delta_{sn} \tag{1}$$

3) Heat transfer coefficient from the pumped product to the soil is infinite. This assumption is valid for metal pipeline without thermal insulation, which is discussed in the article [21].

4) The problem is solved in a stationary setting. This assumption is valid for a pipeline older than 3 years [2, 7].

Then the mathematical model of the underground pipeline and the boundary conditions are:

$$\begin{cases} \lambda_s \left(\dfrac{\partial^2 T}{\partial x^2} + \dfrac{\partial^2 T}{\partial y^2} \right) = 0 \\ -\lambda_s \left.\dfrac{\partial T}{\partial x}\right|_{x=0,3H} = 0 \\ -\lambda_s \left.\dfrac{\partial T}{\partial y}\right|_{y=-H} = 0 \\ -\lambda_s \left.\dfrac{\partial T}{\partial y}\right|_{y=0} = \alpha \left(T - T_{ex} \right) \\ T\big|_L = T_{pr} \end{cases} \tag{2}$$

The first equation in system (2) is the stationary heat equation [2, 7]. The second and third equations determine the absence of the thermal influence of the pipeline to the soil outside the simulation area [27, 28]. The fourth equation determines the heat exchange of the pipeline with the atmosphere through the snow cover according to the Newton's law of cooling [21, 27, 28]. The last equation sets the temperature on the surface of the pipeline [21].

The result of the calculations is the heat flow from the pipeline to the atmosphere [17]:

$$q = \int_L -\lambda_s \frac{\partial T}{\partial n} dL \tag{3}$$

Next, this problem is transformed to a dimensionless form using the following expressions:

$$\begin{cases} T = \left(T_{pr} - T_{ex} \right) \tilde{T} + T_{ex} \\ y = D\tilde{y} \\ x = D\tilde{x} \\ H = D\tilde{H} \\ L = D\tilde{L} \\ T_{ex} = 0 \\ \dfrac{\partial T}{\partial n} = \dfrac{\left(T_{pr} - T_{ex} \right)}{D} \dfrac{\partial \tilde{T}}{\partial \tilde{n}} \\ q = \left(T_{pr} - T_{ex} \right) \lambda_s K \end{cases} \tag{4}$$

Next, the Eqs. (2), (3) are represented in the terms of dimensionless variables from (4):

$$\begin{cases} \lambda_s\left(\dfrac{\partial^2\tilde{T}}{\partial\tilde{x}^2}+\dfrac{\partial^2\tilde{T}}{\partial\tilde{y}^2}\right)=0 \\ -\lambda_s\left.\dfrac{\partial\tilde{T}}{\partial\tilde{x}}\right|_{\tilde{x}=0,3\tilde{H}}=0 \\ -\lambda_s\left.\dfrac{\partial\tilde{T}}{\partial\tilde{y}}\right|_{\tilde{y}=-\tilde{H}}=0 \\ -\left.\dfrac{\partial\tilde{T}}{\partial\tilde{y}}\right|_{\tilde{y}=0}=\dfrac{\alpha D}{\lambda_s}\tilde{T} \\ \tilde{T}\Big|_{\tilde{L}}=1 \\ K=\int\limits_{\tilde{L}}-\dfrac{\partial\tilde{T}}{\partial\tilde{n}}d\tilde{L} \end{cases} \tag{5}$$

Thus, the problem (2) is transformed to dimensionless form (5). Here there is only two independent dimensionless variables for geometric and thermal similarity (dimensionless laying depth k_h and Nusselt number Nu):

$$k_h = 2h_0/D \tag{6}$$

$$\mathrm{Nu} = \frac{\alpha D}{\lambda_s} \tag{7}$$

Expressions (6) and (7) are the only independent variables in the considered problem. They were varied in the multivariate numerical study. The main aim of the numerical study was to determine the dependence of the dimensionless heat transfer coefficient K on the Nusselt number Nu and dimensionless laying depth k_h:

$$K = f(\mathrm{Nu}, k_h) \tag{8}$$

4. Accuracy of the Numerical Method and the Size of the Calculation Domain

The solution of the boundary value problem (4) is carried out using the finite element method. The Nusselt number Nu ranged from 0.0005 to 100. The dimensionless laying depth k_h ranged from 1.05 to 100.

The minimum size of the finite elements is $\pi D/30$ and corresponds to the surface of the pipe. The maximum size is $H/8$. The growth rate of the size of finite elements is 1.1. In total 6019 Lagrange elements were in the computational domain. The convergence of the finite element method was verified by increasing the order of finite elements from 1st to 3rd. The maximum calculation error after increasing the order of the elements from the 1st to the 2nd was 0.14%. The maximum calculation error after increasing the order of the elements from the 2nd to the 3rd was 0.002%. Thus, the selected first-order Lagrange finite element mesh density provides a calculation error not more than 0.15%.

Numerical calculation is performed using an example of a pipeline with a diameter of D = 0.1 m. The authors studied the effect of the size of the computational domain on the error of the numerical method (edge effect). According to the results the size of the computational domain has the greatest influence in case of the minimum value of the Nusselt number Nu = 0.0005. This is due to the very low coefficient α (high snow cover), which blocks the flow of heat and causes it to propagate sideways from the pipeline. Thus, the size of the computational domain should be significantly increased. Figure 2 shows the results of calculation of the heat transfer coefficient depending on the size of the computational domain H.

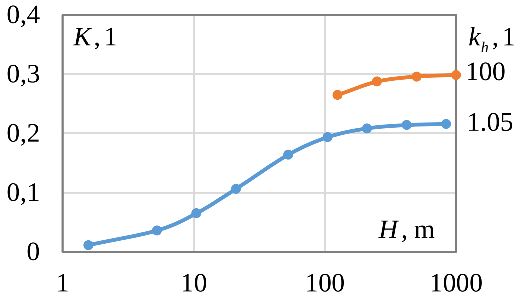

Fig. 2. The influence of the size of the computational domain *H* on the accuracy of calculating the dimensionless heat transfer coefficient *K*.

The size of the computational domain is about H = 840 m provides good accuracy of the calculation of the dimensionless heat transfer coefficient K. The calculation error is approximately 1%. Therefore, in the multivariate numerical study the size of the computational domain was fixed equal to H = 840 m, and the diameter equal to D = 0.1 m.

5. Multivariate Numerical Study and Approximation of Results

Numerical study was performed with the following parameters of the mathematical model: D = 0.1 m; H = 840 m; $\lambda_s \in [0.1,10]$ W m^{-1} K^{-1}; $\alpha \in [0.05,100]$ W m^{-2} K^{-1}; $k_h \in [1.05,100]$, Nu $\in [0.0005,100]$. 490 calculations were performed in total. The calculation results were approximated by formulas (9)-(11) with the error of not more than ± 1.3% in the range Nu $\in [0.0005,100]$; $k_h \in [1.05,100]$ (further Forchheimer-Markov formula):

$$K_1 = 2\pi\left(\ln\left(\left(k_h + 2/\mathrm{Nu}\right) + \sqrt{\left(k_h + 2/\mathrm{Nu}\right)^2 - 1}\right) + R_{ad}\right)^{-1} \quad (9)$$

$$R_{ad} = 1.325\,log_{10}\left(1 + 10^{-1.9\left(P^{0.868} - 2.9\right)}\right) \quad (10)$$

$$P = \log_{10}\left(\mathrm{Nu}\right) + 4 + 0.0258\log_{10}^2\left(k_h\right) + 0.9029\log_{10}\left(k_h\right) - 0.0191 \quad (11)$$

The Forchheimer-Markov formula differs from the Arons-Kutateladze formula (12) by the additional dimensionless thermal resistance coefficient R_{ad} [20]:

$$K_2 = 2\pi\left(\ln\left(\left(k_h + 2/\mathrm{Nu}\right) + \sqrt{\left(k_h + 2/\mathrm{Nu}\right)^2 - 1}\right)\right)^{-1} \quad (12)$$

The coefficient R_{ad} in the Forchheimer-Markov additionally reduces heat flow from the pipeline to the atmosphere. This effect is especially significant when the Nusselt number Nu <1. Figure 3 shows a comparison of the results of a numerical experiment and approximation by the formula (10) - (11). It can be seen that formulas (10)-(11) approximates R_{ad} with good accuracy.

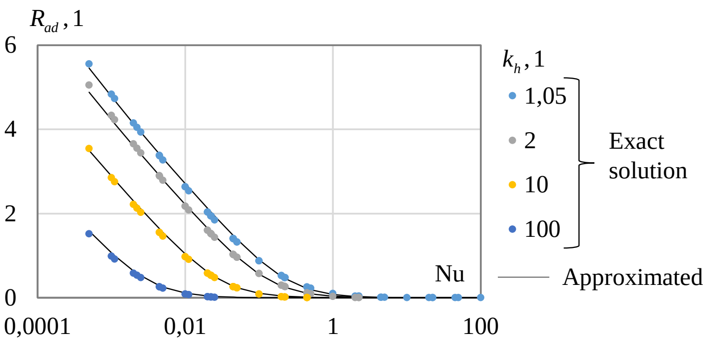

Fig. 3. Dependence of the additional thermal resistance coefficient R_{ad} on the Nusselt number Nu and dimensionless laying depth k_h.

The additional thermal resistance coefficient increases when Nusselt number becomes less than 1. This is especially noticeable in case of small dimensionless laying depth of pipeline. The next paragraph will show that the influence of R_{ad} to the K_1 is significant.

6. Analysis of the Forchheimer-Markov Formula and Discussion

The dependence of the dimensionless heat transfer coefficients K_1 and K_2 on the laying depth of pipeline is presented on the Figs. 4-6.

The authors note the need for in-depth analysis of Figs. 4 and 5. When Nu < 0.1 an increase in the laying depth of the pipeline leads to increasing of heat flux into the atmosphere. It may seem very strange, but the explanation is obvious. The main reason is the stretching of temperature field along the *x* axis for small values of Nu (corresponds to small values of α). Thus, the heat flux from the pipeline to the atmosphere is proportional to the laying depth of the pipeline in the conditions of high thermal resistance of snow cover.

The Arons-Kutateladze formula (12) cannot predict this phenomenon, because term (10) is not taken into account. The error of the Arons-Kutateladze formula at k_h = 2 is: 56% at Nu = 0.0005; 41% at Nu = 0.005; 22% at Nu = 0.05; 4% at Nu = 0.5. Thus, the Arons-Kutateladze formula has an error of about 50% at high thermal resistance of the snow cover.

The new Forchheimer-Markov formula (9)-(11) allows taking into account this phenomenon and therefore is more accurate. The error of the Forchheimer-Markov formula does not exceed 1.3% in the range of Nu ∈ [0.0005,100] and k_h ∈ [1.05,100].

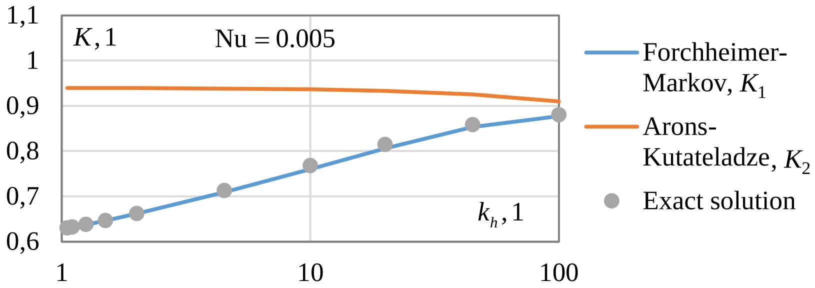

Fig. 4. The dependence of dimensionless heat transfer coefficient *K* on dimensionless laying depth k_h at Nu=0.005.

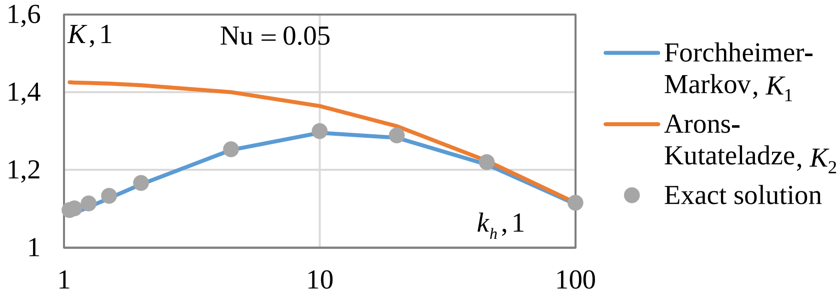

Fig. 5. The dependence of dimensionless heat transfer coefficient *K* on dimensionless laying depth k_h at Nu=0.05.

At higher Nusselt number (more than 1) the Arons-Kutateladze and the Forchheimer-Markov formulas show the same result, because the stretching of temperature fields along the x axis is not significant (Fig. 6).

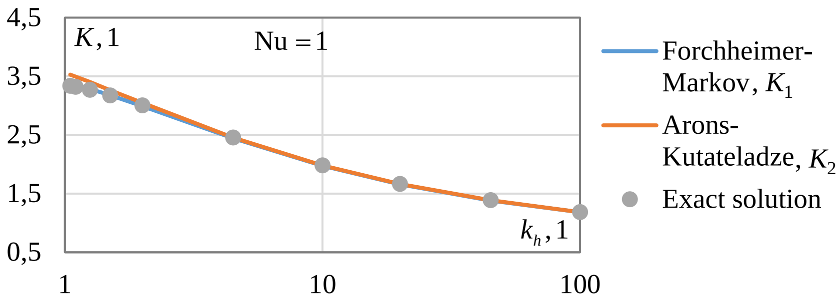

Fig. 6. The dependence of dimensionless heat transfer coefficient *K* on dimensionless laying depth k_h at Nu=1.

The authors present the analysis of the dimensionless heat transfer coefficients K_1 and K_2 using the example of three pipelines: Bovanenkovo-Ukhta gas pipeline (D = 1.42 m), Urengoy-Surgut condensate pipeline (D = 0.72 m) and the Yamburg-Urengoy condensate pipeline (D = 0.32 m). The thermal conductivity of soils is about λ_s = 1.8 W m^{-1} K^{-1}, the thermal conductivity of the snow cover is about λ_{sn} = 0.18 W m^{-1} K^{-1}. The thickness of the snow cover δ_{sn} = 0.75 m. The depth of the pipeline h_0 = 1 m. Table 1 shows the initial data and the results calculations.

Table 1. Initial data and results of calculation.

Pipeline	α	Nu	k_h	K_1	K_2	$(K_2\text{-}K_1)/K_1\cdot 100\%$
Bovanenkovo-Ukhta	0.24	0.189	1.41	1.75	1.98	13%
Urengoy-Surgut	0.24	0.096	2.77	1.46	1.63	14%
Yamburg-Urengoy	0.24	0.043	6.15	1.35	1.23	10%

Table 1 shows that Arons-Kutateladze formula overestimates the heat transfer coefficient by 10-14% as compared with Forchheimer-Markov formula. In this case, authors consider the Forchheimer-Markov formula is more preferable than the Arons-Kutateladze formula. The main reason is that the Forchheimer-Markov formula corresponds to the exact solution of the heat equation with error not more than 1.3% in the range of Nu ∈ [0.0005,100] and k_h ∈ [1.05,100]. Thus, the total error of the Forchheimer-Markov formula consists of three parts: the edge effect is 1%, the error of the numerical method (finite element method) is 0.15%, and the approximation error is 1.3%. The total error is estimated by the formula (1.01*1.0015*1.0134-1)*100% = 2.5%.

At the same time, the Arons-Kutateladze formula is much simpler than the Forchheimer-Markov formula. Therefore, the authors derived the formula (13) for the possible field of application of the Arons-Kutateladze formula and the Forchheimer-Markov formula:

$$\begin{cases} K = K_1,\ if\ \ k_h \le 1.77/\mathrm{Nu}^{0.75}, \mathrm{Nu} > 0.0005, k_h \in [1.05,100] \\ K = K_2,\ if\ \ k_h > 1.77/\mathrm{Nu}^{0.75}, \mathrm{Nu} > 0.0005, k_h \in [1.05,100] \end{cases} \tag{13}$$

If the laying depth is more than critical, then the calculation error by the Arons-Kutateladze formula (12) does not exceed 3%. If the laying depth is less than critical, then the Forchheimer - Markov formula (9)-(11) recommended for the calculation.

7. Conclusions

The mathematical model and calculation scheme for determining the heat flux from the pipeline to the atmosphere through the soil and snow cover has been developed. The mathematical model is transformed to a dimensionless form with two independent variables - the Nusselt number and dimensionless depth of laying of the pipeline. The snow cover was presented in a classic way - using the convective heat transfer coefficient.

The authors studied the influence of edge effects to the accuracy of numerical modeling. The minimum size of the computational domain H = 840 m provides an error not more than 1% in the case of Nusselt number Nu = 0.0005, pipeline diameter D = 0.1 m, dimensionless depth of laying k_h from 1.05 to 100. In a case of Nu > 0.0005 the error is much smaller. The error of numerical method (finite element method, first-order Lagrange elements) is 0.15%.

The Forchheimer-Markov formula (9)-(11) is derived for the dimensionless heat transfer coefficient. The formula describes the heat flux from the pipeline to the atmosphere through the snow cover. The Forchheimer-Markov formula approximates the results of numerical study with error of not more than 1.3% in the range of the Nusselt number Nu ∈ [0.0005,100] and the dimensionless depth of laying $k_h \in [1.05,100]$. In addition, the field of application of the Forchheimer-Markov formula and the Arons-Kutateladze formula was obtained.

The study of the heat flow from the pipeline to the atmosphere for the three existing main pipelines showed that Arons-Kutateladze formula gives an error of about 10-14% (Table 1). The authors recommend using the Forchheimer-Markov formula instead of the Arons-Kutateladze formula, because it gives the value corresponding to the exact solution of heat transfer problem (2) with total error is not more than 2.5%.

Nomenclatures

D	diameter of pipeline, m
H	size of computational domain, m
$\tilde{H}$	dimensionless size of computational domain, 1
h_0	laying depth, m
K	dimensionless heat transfer coefficient, 1
K_1	Forchheimer-Markov dimensionless heat transfer coefficient,1
K_2	Arons-Kutateladze dimensionless heat transfer coefficient, 1^1
k_h	dimensionless depth of laying of the pipeline, 1
L	pipe surface curve, m
$\tilde{L}$	dimensionless pipe surface curve, 1
Nu	Nusselt number, 1
n	normal to the pipeline surface curve
$\tilde{n}$	normal to the dimensionless pipeline surface curve
P	exponent parameters, 1
q	heat flow from pipeline to atmosphere, W m^{-1}
R_{ad}	additional thermal resistance coefficient, 1
T	temperature of soil, K
$\tilde{T}$	dimensionless temperature of soil, 1
T_{ex}	temperature of air, K
T_{pr}	temperature of pipeline, K
x	abscissa axis coordinate, m
$\tilde{x}$	dimensionless abscissa axis coordinate, 1
y	ordinate axis, m
$\tilde{y}$	dimensionless ordinate axis coordinate, 1

Greek Symbols

α	convective heat transfer coefficient on the surface of the ground, $W \cdot m^{-2} \cdot K^{-1}$
δ_{sn}	snow thickness, m
λ_{sn}	thermal conductivity of snow, W $m^{-1}K^{-1}$
λ_s	thermal conductivity of soil, W $m^{-1}K^{-1}$

References

1. Bronfenbrener, L.; and Korin, E. (1999). Thawing and refreezing around a buried pipe. *Chemical Engineering and Processing: Process Intensification*, 38(3), 239-247.

2. Lisin, Y.V.; Sapsay, A.N.; Pavlov, V.V.; Zotov, M.Y.; and Kaurkin, V.D. (2014). Selection optimal technical solutions for laying the oil pipeline to ensure reliable operation of the pipeline system «Zapolyarye - Purpe» on the basis of forecasting thermotechnical calculations. *Transportation and Storage of Petroleum Products and Hydrocarbons*, 1(1), 3-7.
3. Li, G.; Wang F.; and Ma, W. (2018). Field observations of cooling performance of thermosyphons on permafrost under the China-Russia crude oil pipeline. *Applied Thermal Engineering*, 141(1), 688-696.
4. Wang, F.; Li, G.; Ma, W.; Wu, Q.; Serban, M.; Vera, S.; Alexandr, F.; Jiang, N.; and Wang, B. (2019). Pipeline-permafrost interaction monitoring system along the China-Russia crude oil pipeline. *Engineering Geology*, 254(1), 113-125.
5. Wang, F.; Li, G.; Ma, W.; Mao, Y.; Mu, Y.; Serban, M.; and Cai, Y. (2019). Permafrost warming along the Mo'he-Jiagedaqi section of the China-Russia crude oil pipeline. *Journal of Mountain Science*, 16(2), 285-295.
6. Dwight, R.A.; Cairns, D.M.; and Giguère, N. (2018). The trans-Alaska pipeline system facilitates shrub establishment in northern Alaska. *Arctic*, 71(3), 249-258.
7. Nikolaeva, M.V.; Struchkova, G.P.; and Atlasov, R.A. (2018). Modeling and calculation of the stress-strain state of buried pipelines taking into consideration the soil ice. *Proceedings of the 12th International Conference on Mechanics, Resource and Diagnostics of Materials and Structures*. Ekaterinburg, Russia, 1-8.
8. Liang, Z.; Lu, X.; and Zhang, J. (2019). Thermal vertical buckling of surface-laid submarine pipelines on a sunken seabed. *Ocean Engineering*, 173(1), 331-344.
9. Wang, Z.; Heijden, G.H.M.; and Tang, Y. (2018). Analytical study of third-mode lateral thermal buckling for unburied subsea pipelines with sleeper. *Engineering Structures*, 168, 447-461.
10. Lazarev, S.A.; Pulnikov, S.A.; and Sysoev, Y.S. (2016). Evaluation of the technical condition of the linear part of main gas pipelines in the zones of significant spatial deformation. *Gas Industry*, 9(1), 84-90.
11. Fedorov, Y.Y.; Savvina, A.V.; Vasilyev, S.V.; and Rodionov, A.K. (2018). Gas pipelines with a pressure of up to 1.2 MPa, made from reinforced polyethylene pipes, under conditions of cold climate and permafrost soils. *Proceedings of the 12th International Conference on Mechanics, Resource and Diagnostics of Materials and Structures*. Ekaterinburg, Russia, 1-7.
12. Bondarev, E.A.; Rozhin, I.I.; and Argunova, K.K. (2019). Generalized mathematical model of hydrate formation in gas pipelines. *Journal of Applied Mechanics and Technical Physics*, 60(3), 503-509.
13. Sunagatullin, R.Z.; Karimov, R.M.; and Dmitriev, M.E. (2019). Study of heat-hydraulic efficiency of asphalt-resinous paraffinic oil deposits in field and trunk pipelines. *IOP Conference Series: Earth and Environmental Science*, 272(2), 1-8.
14. Li, H.; Lai, Y.; and Li, L. (2020). Impact of hydro-thermal behaviour around a buried pipeline in cold regions. *Cold Regions Science and Technology*, 171(1), 1-15.
15. Markov, E.; Pulnikov, S.; and Sysoev, Y. (2020). Operation problems of the cold condensate pipeline in heaving soils and arctic climate. *Transportation Soil Engineering in Cold Regions*, 49(1), 183-195.

16. Markov, E.V.; Pulnikov, S.A.; and Sysoev, Y.S. (2018). Evaluation of the effectiveness of ring thermal insulation for protecting a pipeline from the heaving soil, *Journal of Engineering Science and Technology*, 13(10), 3344-3358.
17. Kutateladze, S.S. (1979). *Basics of heat transfer theory*. (5th ed.). Moscow: Atomizdat.
18. Chernikin, V.I. (1958). *Transfer of viscous and solidifying oils*. (1sted.). Moscow: Gostoptehizdat.
19. Garris, N.A.; Rusakov, A.I.; and Baykova, L.R. (2018). New approach to estimation of thermal conductivity coefficient for underground pipeline forming a thawing halo in permafrost. *Journal of Physics*, 1111(1), 1-7.
20. Polovnikov, V.Y. (2018). Thermal regimes and heat losses of underground pipelines taking into account the actual conditions of heat exchange on the external circuit of interaction. *Bulletin of Tomsk Polytechnic University. Georesource engineering*, 329(1), 124-131.
21. Yakupov, A.U.; Voronin, K.S.; and Cherentsov, D.A. (2019). Temperature condition of a stopped underground oil pipeline. *Proceedings of the International Conference on Extraction, Transport, Storage and Processing of Hydrocarbons and Minerals.* Tyumen, Russia, 1-6.
22. Korotkov, A.A.; and Kislov, A.S. (2019). Improving the accuracy of calculating the temperature of a pipeline wall operated in harsh climatic and natural conditions (Russian). *Oil Industry*, 9(1), 118-120.
23. Stepanov, A.V.; and Egorova, G.N. (2017). Evaluation of the radiation coefficient effect in total heat transfer between network pipelines and water pipes in joint installation. *Science and Education*, 4(1), 93-98.
24. Zhang, S.; Teng, J.; He, Z.; and Sheng, D. (2016). Importance of vapor flow in unsaturated freezing soil: a numerical study. *Cold Regions Science and Technology*, 126(1), 1-9.
25. He, Z.; Zhang, S.; Teng, J.; Yao, Y.; and Sheng, D. (2018). A coupled model for liquid water-vapor-heat migration in freezing soils. *Cold Regions Science and Technology*, 148(1), 22-28.
26. Kalyuzhnyy, I.L.; and Lavrov, S.A. (2012). *Hydrophysical processes in the catch basin: Experimental studies and modeling* (1st ed.). St. Peterburg: Nestor-Istoriya.
27. Gunar, A.Yu.; Khrustalev, L.N.; Khilimonyuk, V.Z.; Emelyanova, L.V.; Trofimov, V.V.; Zhang, A.A.; Surikov, V.I.; and Korotkov, A.A. (2017). The method of selecting of project solutions for laying the linear part of oil pipeline in permafrost. *Earth's Cryosphere*, XXI(6), 84-94.
28. Markov, E.V.; Pulnikov, S.A.; and Sysoev, Y.S. (2018). Comparison of calculating methods of the heat transmission parameters for underground pipeline in a wide range of product temperature. *International Journal of Civil Engineering and Technology*, 9(7), 1903-1909.