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Numerical analysis of a heat loss of channel-free heat pipeline in the real application conditions

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Abstract. The results of mathematical modeling of heat regimes of channel-free heat pipeline, as well as numerical analysis of heat loss of channel-free heat pipeline in conditions of freezing ground and the presence of snow cover area were given. The laws of heat transfer in the system and the factors that influence the intensification of heat losses are shown. It was revealed that the normative calculation method of heat loss of channel-free heat pipeline gives overestimated values of heat loss.

1. Introduction

There are many publications on research to develop and improve the efficiency of heating systems in the modern scientific literature [1–11]. Publication of a heat loss of heat pipeline [7–11] is very important.

One of the promising approaches to study of modes of heat pipeline in the real application conditions is a numerical simulation. This makes it possible to take account of different effects and processes which lead to an intensification of heat and mass transfer in under consideration systems.

The aim of the present paper is a mathematical modeling of thermal regimes and numerical analysis of a heat loss of channel-free heat pipeline in conditions of freezing ground and the presence of snow cover.

2. Problem statement

We consider a typical channel-free heat pipeline. Pipes insulated with a polyurethane foam and a protective waterproofing layer of a polyethylene [11].

A channel-free heat pipeline is operated in the real application conditions (There are a ground freezing and a presence of snow cover). Figure 1 shows a scheme of decision domain.

For the domain under consideration (Fig. 1) we solve a 2D linear and stationary problem of heat transfer in conditions of ground freezing and a presence of snow cover. Formulating the problem, we used the following assumptions:

1. The heat transfer processes in the internal and the external environment are disregarded.
2. Thermophysical characteristics of materials used in the analysis are constant and known values.
3. There is an ideal thermal contact conditions at the boundaries.
4. The heat in the decision domain (Fig. 1) is transferred only by conduction.

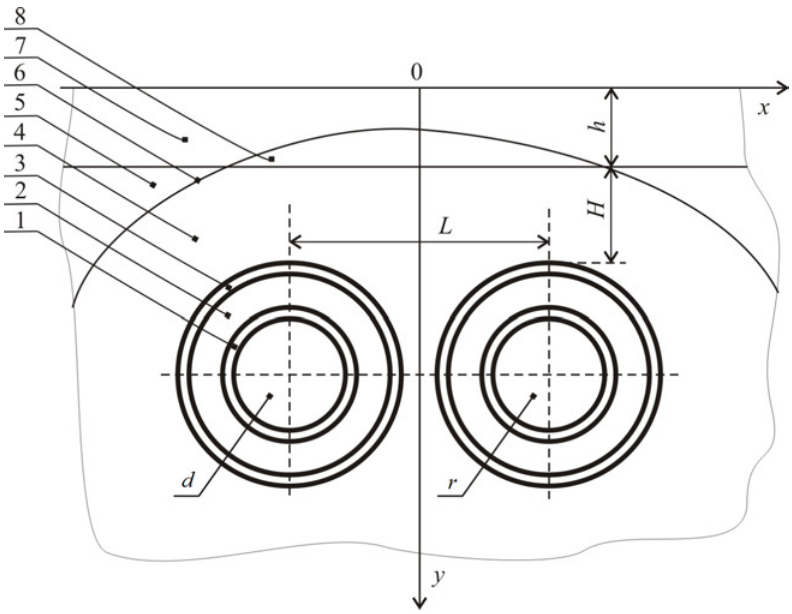

Figure 1. A scheme of decision domain: 1 – metal wall of the heat pipeline; 2 – insulating layer; 3 – waterproofing layer; 4 – melted ground; 5 – frozen ground; 6 – boundary between melted and frozen zones; 7 – frozen snow; 8 – melted snow; d, r – direct and return heat pipelines; H – distance from the ground surface to the upper layers of waterproofing points; L – distance between axes of heat pipelines; h – thickness of snow cover.

The listed assumptions, on the one hand, do not impose constrains of principle on the physical model of the system (Fig. 1), but, on the other hand, allow one to simplify in a certain manner the algorithm and method for solving the posed problem.

3. Mathematical model

In the proposed statement, the heat transfer process in the considered decision domain (Fig. 1) in a general formulation is described:

$$\nabla^2 T_{d,p} = 0, \tag{1}$$

$$\nabla^2 T_{r,p} = 0, \tag{2}$$

$$\nabla^2 T_{d,i} = 0, \tag{3}$$

$$\nabla^2 T_{r,p} = 0, \tag{4}$$

$$\nabla 2 T_{d,h} = 0, \tag{5}$$

$$\nabla^2 T_{r,h} = 0, \tag{6}$$

$$\nabla^2 T_{s,g} = 0, \tag{7}$$

$$\nabla^2 T_{f,g} = 0, \tag{8}$$

$$\nabla^2 T_{m,sn} = 0, \tag{9}$$

$$\nabla^2 T_{c,sn} = 0. \tag{10}$$

$$T_{d,p,1} = T_{d,in} = \text{const}, \tag{11}$$

$$T_{r,p,1} = T_{r,in} = \text{const}. \tag{12}$$

$$\lambda_p \,\text{grad}(T_{d,p,2}) = \lambda_i \,\text{grad}(T_{d,i,2}); T_{d,p,2} = T_{d,i,2}, \tag{13}$$

$$\lambda_p \,\text{grad}(T_{r,p,2}) = \lambda_i \,\text{grad}(T_{r,i,2}); T_{r,p,2} = T_{d,i,2}, \tag{14}$$

$$\lambda_i \,\text{grad}(T_{d,i,3}) = \lambda_h \,\text{grad}(T_{d,h,3}); T_{d,i,3} = T_{d,h,3}, \tag{15}$$

$$\lambda_i \,\text{grad}(T_{r,i,3}) = \lambda_h \,\text{grad}(T_{r,h,3}); T_{r,i,3} = T_{r,h,3}, \tag{16}$$

$$\lambda_h \,\text{grad}(T_{d,h,4}) = \lambda_{s,g} \,\text{grad}(T_{d,s,g,4}); T_{d,h,4} = T_{d,s,g,4}, \tag{17}$$

$$\lambda_h \,\text{grad}(T_{r,h,4}) = \lambda_{s,g} \,\text{grad}(T_{r,s,g,4}); T_{r,h,4} = T_{r,s,g,4}, \tag{18}$$

$$\lambda_{s,g} \,\text{grad}(T_{s,g,5}) = \lambda_{f,g} \,\text{grad}(T_{f,g,5}); T_{s,g,5} = T_{f,g,5}, \tag{19}$$

$$\lambda_{f,g} \,\text{grad}(T_{f,g,6}) = \lambda_{m,sn} \,\text{grad}(T_{m,sn,6}); T_{f,g,6} = T_{m,sn,6}, \tag{20}$$

$$\lambda_{m,sn} \,\text{grad}(T_{m,sn,7}) = \lambda_{c,sn} \,\text{grad}(T_{c,sn,7}); T_{m,sn,7} = T_{c,sn,7}. \tag{21}$$

$$-\lambda_{c,sn} \,\text{grad}(T_{c,sn,8}) = \alpha(T_{c,sn,8} - T_{ex}). \tag{22}$$

$$\text{grad}(T_{f,g}) = 0, x \to \pm\infty, \tag{23}$$

$$\text{grad}(T_{s,g}) = 0, x \to \pm\infty; y \to -\infty, \tag{24}$$

$$\text{grad}(T_{m,sn}) = 0, x \to \pm\infty, \tag{25}$$

$$\text{grad}(T_{c,sn}) = 0, x \to \pm\infty; y \to -\infty. \tag{26}$$

4. Method of solution and initial data

The system of Eqs. ((1)–(26)) was solved by the finite element method [12], using the Galerkin approximation [13]. The investigations were carried out on a nonuniform finite-element mesh. The number of elements was chosen from conditions of convergence of solution, the mesh was made denser by the Delaunay method [12, 13].

Table 1 contains values [10, 11] of thermophysical characteristics, which were used in the numerical investigations of thermal conditions of the system under consideration (Fig. 1).

In spite of the fact that in statement of the problem it was assumed to use an infinite-size domain (Eqs. (23)–(26)), in the numerical analysis of heat loss we used a calculation domain of 6 m in depth and 5 m laterally from the symmetry axis. The sizes of the calculation domain were chosen on the basis of a series of preliminary numerical experiments in such a manner that the relative change of the temperature gradients at the domain boundary does not exceed 0.5%.

Table 1. Thermophysical characteristics.

Characteristic	Waterproofing layer	Insulating layer	Metal wall of the heat pipeline	Ground				Snow	
				Clayey		Sandy			
				Melted	Frozen	Melted	Frozen	Frozen	Melted
λ, [W/(m · K)]	0.33	0.033	50.2	1.1	1.3	2.3	3.7	0.35	0.64
c, [J/(kg · K)]	2200	1470	462	1231	959	1486	1005	2100	2100
ρ, [kg/m^3]	920	50	7700	1700	1700	2000	2000	350	500

Table 2. Results of numerical simulation.

Ground	Sandy				Clayey			
α, [W/(m^2 · K)]	5	10	20	30	5	10	20	30
Q_0, [W/m]	137.40	140.48	142.10	142.65	100.48	102.15	103.01	103.30
Q_1, [W/m]	124.39	126.79	128.36	128.91	93.07	94.63	95.42	95.69
Q_2, [W/m]	144.70	149.94	152.27	153.21	102.17	104.30	105.26	105.62
$\frac{Q_2-Q_0}{Q_2}$ 100%	5.04	6.30	6.67	6.89	1.65	2.06	2.14	2.19
$\frac{Q_2-Q_1}{Q_2}$ 100%	14.03	15.44	15.70	15.86	8.91	9.27	9.35	9.40
$\frac{Q_0-Q_1}{Q_0}$ 100%	9.47	9.74	9.67	9.63	7.37	7.36	7.36	7.36

The analysis was carried out for pipelines with a diameter of nominal bore of 600 mm; the pipeline was manufactured from steel 10 (thickness 8 mm) with thermal insulation from polyurethane foam (40 mm thick) and a protective waterproofing layer of a polyethylene (2 mm thick).

The distances from the ground surface to the upper layers of waterproofing points and between axes of heat pipelines were H = 2 m and L = 1.3 m (Fig. 1). The thickness of snow cover was h = 185 mm (Fig. 1).

The temperature of the inner surface of pipes were Td, in = 338 K and Tr, in = 323 K. The ambient temperature was Tex = 264.2 K. The coefficient of heat transfer α was from 5 to 30 W/(m^2 · K).

5. Results of numerical simulation

The main results of numerical modeling of thermal conditions of the system under consideration (Fig. 1) are listed in Table 2 and in Fig. 2.

Validity and reliability of the obtained results follow from tests of the methods for convergence and stability of solutions on multiple meshes, fulfillment of the energy balance conditions at boundaries of the calculation domain. The relative calculation error in all versions of the numerical analysis did not exceed 0.5%, which is acceptable for investigations of thermal conditions of the system under consideration (Fig. 1).

Table 2 lists the results of numerical experiments of the heat loss of channel-free heat pipeline in the real application conditions Q_1 (There are a ground freezing and a presence of snow cover), Q_2 (There is not a snow cover) and Q_0 (There are not a ground freezing and a presence of snow cover).

The numerical experimental results in Table 2 allow us to make the inference about the expected increase of the heat loss of channel-free heat pipeline at presence a high thermal conductivity ground. The data presented in Table 2 allow us to make the following conclusions:

1. The change of heat transfer coefficient α from 5 to 30 W/(m^2 · K) increases the heat loss of channel-free heat pipeline by not more than 3.5%.
2. The ground freezing increases the heat loss of channel-free heat pipeline by 5.04–6.89% for a sandy ground and by 1.65–2.19% for a clayey ground.

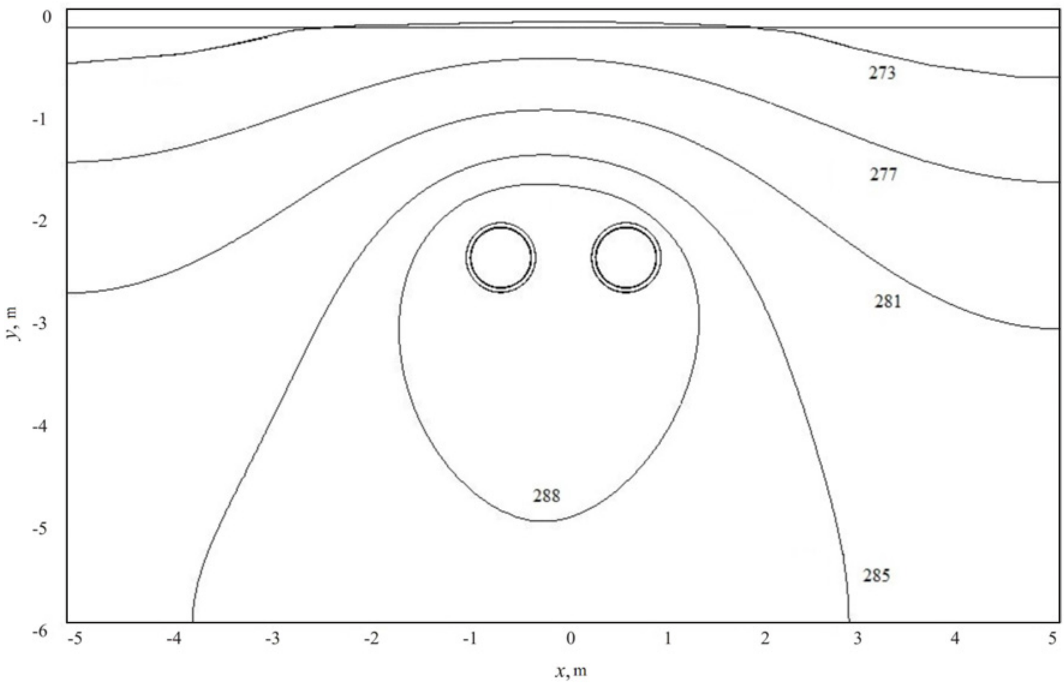

Figure 2. Temperature field of the ground in the region of channel-free heat pipeline.

3. The snow cover decreases the heat loss of channel-free heat pipeline by 14.03–15.86% for a sandy ground and by 8.91–9.40% for a clayey ground.
4. The total change of the heat loss of channel-free heat pipeline in the real application conditions is by about 7% for a clayey ground and 9% for a sandy ground.

Figure 2 represent a typical temperature field of the ground in the region of channel-free heat pipeline.

It was found that the isothermal lines (Fig. 2) become denser near the ground surface immediately above the heat pipeline and are sparser as the distance from the heat pipeline grows; this represents the real operation conditions of the heat pipeline system and qualitatively complies with results of investigations represented in [9, 10].

6. Conclusion

We have carried out numerical analysis of thermal regimes and numerical analysis of heat loss of channel-free heat pipeline in the real application conditions (There are a ground freezing and a presence of snow cover). It has been shown that application of the proposed approach enables comprehensive analysis of thermal regimes of the system under consideration.

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Notations

T – temperature, K; λ – thermal conductivity, $\mathrm{W/(m \cdot K)}$; c – heat capacity, $\mathrm{J/(kg \cdot K)}$; ρ – density, $\mathrm{kg/m^3}$; α – heat transfer coefficient, $\mathrm{W/(m^2 \cdot K)}$.

Indices: d – direct heat pipeline; r –return heat pipeline; p – pipe; i – insulation; h – waterproofing; g – ground; s, m – melted; c, f – frozen; in – internal; ex – external; sn – snow; 1 – inner surface of the pipe; 2 – 8 partition of borders: "pipe – thermal insulation", "thermal insulation – waterproofing", "waterproofing – melted ground", " melted ground – frozen ground", "frozen ground – melted snow", "melted snow – frozen snow", "frozen snow – environment".

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