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The method to calculate effective area of thermal stabilization system on experimental criteria of heat-mass exchange

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Abstract. The article presents the results of experiment-calculated determination of the effective area of the system of thermal stabilization of soil under the oil settler in the zone of permafrost soil. The comparison of the value of the surface area of the cooling tubes calculated with the help of the proposed equation with the surface area of the coil used in the experiment showed the possibility of using the proposed method for calculating the horizontal systems of thermal stabilization of soils under the buildings in the experimental conditions.

1. Introduction

In accordance with the strategy of development of Frigid Zone of the Russian federation, the future of our country is closely connected with the development of areas of Far North, where there are considerable reserves of hydrocarbons [1]. The largest oil and gas producing region of Russia is Western Siberia. Its fuel and energy complex is one of the main components of the state's economy. Exploration of new and improvement of proven hydrocarbon fields in Western Siberia, and especially in Tyumen region, is the task at the national scale [2].

The North of Tyumen region is a territory with low average annual temperatures and permafrost soils extending from 64-63° northern latitude and higher [3, 4]. Below 64-63° northern latitude soils differ in seasonal freezing – thawing. The feature of design and operation of facilities for settling and storage of hot petroleum products in the territories occupied by these soils is the registration and regulation of complex heat transfer in the system "frozen soil– hot tank –environment" [5]. Nowadays one of the most common and effective methods of ensuring the bearing capacity of building foundations and structures in permafrost is the application of thermal stabilization systems of soil base [6, 7, 8].

Errors in calculation may result in loss of the soil bearing capacity that is the cause of accidents and destruction of engineering constructions. Therefore, the study of processes accompanying permafrost freezing and thawing to analyze and prevent the negative consequences is relevant in engineering and scientific investigations [9].

The aim of the work is the experimental modeling of thermal stabilization of soil under the oil settler to defend the oil in the area of permafrost at the ambient temperature of minus 8-10 °C.

2. Description of experimental setup

To study the process of thermal stabilization of frozen soil under the tank with hot oil our experimental setup was created, the general scheme is shown in Figure 1.

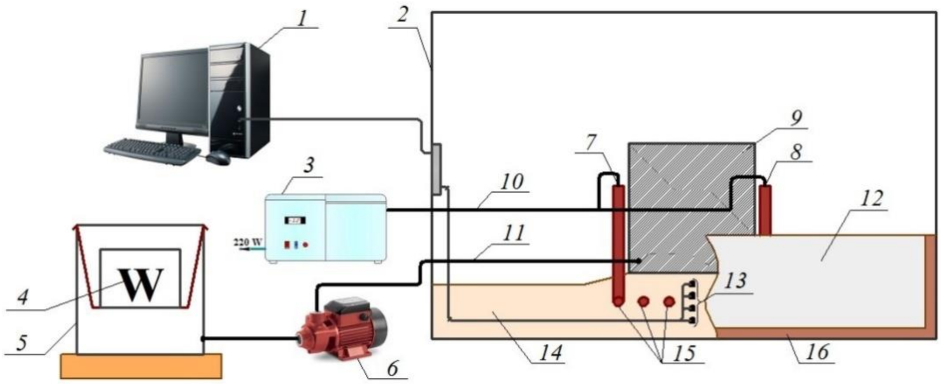

Figure 1. The scheme of the experimental setup: 1 – personal computer; 2 – climatic chamber; 3 – cryostat; 4 – a heating element; 5 – a tank for oil heating; 6 – pump;7 –entrance into the system of cooling pipes; 8 – exit from the system cooling tubes; 9 – tank of a steel vertical; 10 – a hose for pump the coolant; 11 – a hose for pumping heat-transfer agent; 12 – thermal insulation of work area; 13 – temperature sensors; 14 – soil; 15 – system of cooling tubes; 16 – a wooden tray.

The main elements of the experimental setup are the climate chamber Polair, the tray defining work area, a vertical steel tank, the system of heating and pumping a coolant, the soil thermal stabilization system and an automated temperature monitoring system.

The tray of the size 1190×1290×350 mm is located in the climatic chamber. The side walls and the bottom of the tray are thermally insulated with styrofoam plates with a thickness of 100 mm. The amount of soil in the tray is equal to 0.16 m^3.

The tank with the diameter of 520 mm and height of 400 mm is installed on the soil in the center of the tray, between the soil and the bottom of the tank there is a layer of thermal insulation – folgoizolon with a thickness of 4 mm and the thermal conductivity coefficient λ = 0.034 W/(m·K).

The system of heating and circulation of the heat-transfer agent for the tank is located outside the climate chamber.

The thermal stabilization system of soil is represented by a cryostat and the system of cooling pipes laid in the form of a coil made of copper pipes with the diameter of 6.35 mm and with the interaxial pitch of 30 mm. The coil is located in the soil under the tank at the depth of 24 mm. The work of the cooling machine is created by forced circulation of a coolant (antifreeze) in the contour of the cryostat –the coil.

The automated temperature monitoring system includes digital temperature sensors DS18B20 connected to the computer. The soil used in the experiment is represented by sandy loam, thermal properties of which are given in Table 1. The soil moisture is 20 %.

Table 1. Thermal physical properties of soil.

Physical property	frozen soil	thawed soil
Density, kg/m^3	2083.00	
Thermal conductivity, W/(m·K)	3.13	2.38
Specific heat, kJ/(kg·K)	0.95	1.06
Thermal diffusivity, m^2/s	$1.58 \cdot 10^{-6}$	$1.08 \cdot 10^{-6}$

3. The experiment conditions and results

At the primary stage of the experiment in the cryostat there was set the temperature –8.5 °C which was being maintained during several hours till the soil freezing of the temperature. The next stage included the pumping hot heat agent in the tank with the temperature of 30…33 °C. As an initial moment of the experiment there was taken the achievement of positive soil temperature at a depth of occurrence of the coil, which reflects the loss of load capacity and requires additional consumers of thermal energy to compensate heat flow from the tank, which determines the phase transition ice-water. Before the experiment, the initial distribution of soil temperature was obtained (Fig. 2).

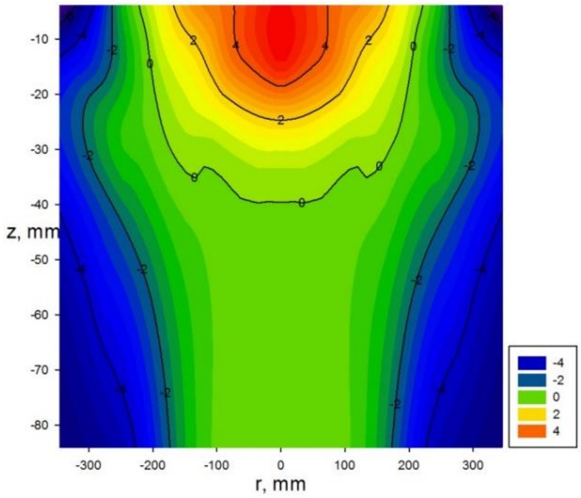

Figure 2. The initial soil temperature field.

The initial temperature of the circulating antifreeze in cooling tubes is −20 °C. Heated by heat exchange with the soil antifreeze entered the cryostat supporting its temperature constant throughout the experiment.

The dynamics of soil temperature field when freezing is shown in Figure 3, 4.

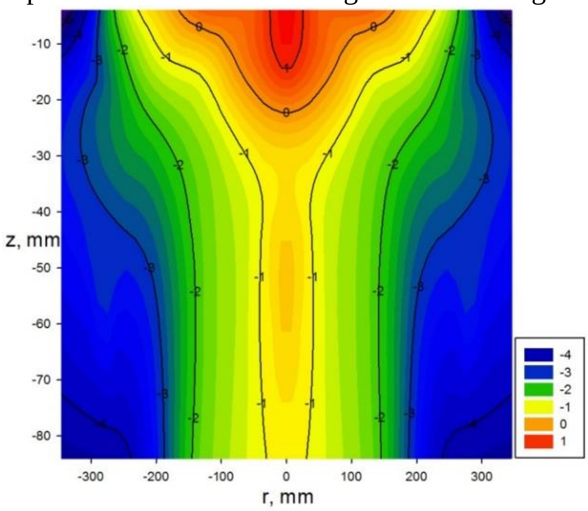

Figure 3. The soil temperature field after 1 hour since the beginning of the freezing process.

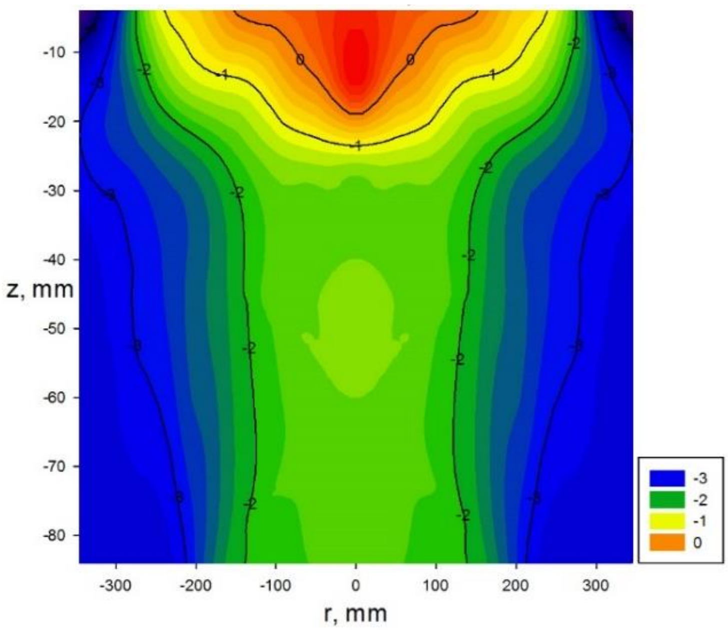

Figure 4. The soil temperature field after 3 hours since the beginning of the freezing process.

4. The heat balance equation

To determine the optimum geometric parameters of thermal stabilization system (the diameter of the cooling tubes, the pitch between the tubes) there was proposed the heat balance equation:

$$k_1 \cdot S_{bot} \cdot \Delta T_1 \cdot \Delta\tau + Q_{ph.t.} = k_2 \cdot \Delta T_2 \cdot \Delta\tau, \quad (1)$$

where k_1– the coefficient of heat transfer from the tank into the soil, W/(m^2·K); S_{bot} – the area of the tank bottom, m^2; ΔT_1 – the mean logarithmetic temperature difference between of the tank bottom and the soil, K; $\Delta\tau$ – the considered period of time, c; $Q_{ph.t.}$ – heat of phase transition, J; ΔT_2 – the mean logarithmetic temperature difference between the of soil and the surface of the cooling tubes, K; k_2 – the heat transfer coefficient from the coolant pipes in the soil, W/K.

The mean logarithmetic temperature difference between the tank bottom and the soil is determined by the expression [10]

$$\Delta T_1 = \frac{(T_{st}^{res} - T_{st}^{s}) - (T_{end}^{res} - T_{end}^{s})}{\ln\frac{T_{st}^{res} - T_{st}^{s}}{T_{end}^{res} - T_{end}^{s}}}, \quad (2)$$

where $T_{st}^{res}, T_{end}^{res}$ – the temperature of the tank bottom in the start and end points of thermal stabilization, respectively, K; T_{st}^{s}, T_{end}^{s} are the temperatures of soil at the start and end points of thermal stabilization, respectively, K.

The mean logarithmetic temperature difference of the soil and the surface of the cooling tubes is determined by the relation similar to the expression (2)

$$\Delta T_2 = \frac{(T_{st}^{s} - T_{st}^{t}) - (T_{end}^{s} - T_{end}^{t})}{\ln\frac{T_{st}^{s} - T_{st}^{t}}{T_{end}^{s} - T_{end}^{t}}}, \quad (3)$$

where T_{st}^{t}, T_{end}^{t} – the surface temperature of the cooling tubes in the start and end points of thermal stabilization, respectively, K.

The heat transfer coefficient from the tank into the soil is defined by the relation [11, 12]

$$\frac{1}{k_1} = \frac{1}{\alpha_1} + \frac{\delta_{bot}}{\lambda_{bot}} + \frac{\delta_{ins}}{\lambda_{ins}}, \tag{4}$$

where $\alpha_1 -$ the heat transfer coefficient by forced convection occurring in the circulation of hot coolant, W/(m^2·K); $\delta_{bot} -$ the thickness of the tank bottom, m; $\lambda_{bot} -$ the thermal conductivity of the material of the tank bottom, W/(m·K); $\delta_{ins} -$ the thickness of the insulation layer under the tank, m; $\lambda_{ins} -$ the coefficient of thermal conductivity of insulation material, W/(m·K).

The heat transfer coefficient by forced convection is equal to

$$\alpha_1 = \frac{Nu \cdot \lambda_1}{h_{load}}, \tag{5}$$

where $\lambda_1 -$ the thermal conductivity coefficient of the heat-transfer agent at its mean temperature, W/(m·K); $h_{load} -$ loading height, m; $Nu -$ Nusselt number determined depending on the Reynolds number for the following relations

$$Nu = 0.15 \cdot Re^{0.33} \cdot Pr^{0.33} \cdot (Gr \cdot Pr)^{0.1} \cdot \left(\frac{Pr}{bot}\right)^{0.25} \text{при} Re \leq 10^4 \tag{6}$$

$$Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.43} \cdot \left(\frac{Pr}{Pr_{bot}}\right)^{0.25} \text{ при } Re > 10^4 \tag{7}$$

Here Pr —the Prandtl number with the average temperature of the heat-transfer agent, dimensionless; $Pr_{bot} -$ the Prandtl number, with an average temperature of the tank bottom, dimensionless; Gr —the Grashof number, dimensionless; $Re -$ the Reynolds number, dimensionless.

The Grashof number is determined by the ratio [13]

$$Gr = \frac{g \cdot (h_{load})^3 \cdot \beta \cdot 0{,}1 \cdot T_1}{\nu^2}, \tag{8}$$

where g – the gravitation acceleration; $\beta -$ the temperature coefficient of volumetric expansion of the heat-transfer agent, K^{-1}; $T_1 -$ the heat-transfer agent temperature, K; $\nu -$ the kinematic viscosity of heat-transfer agent at its mean temperature, m^2/s.

The heat transfer coefficient from a number of cooling tubes in the soil is equal to [14]

$$k_2 = \frac{2 \cdot S_t}{\frac{2}{\alpha_2} + \frac{d_t}{\lambda_s} \ln\left[\frac{2 \cdot s}{\pi \cdot d_t} sh\left(2\pi \frac{h + \lambda_s/\alpha_1}{s}\right)\right]} \tag{9}$$

where S_t – the surface area of the cooling tubes, m^2; α_2 – heat transfer coefficient from the cooling pipes in the soil, W/(m^2·K); λ_s – soil thermal conductivity coefficient, W/(m·K); $d_t -$ pipe diameter, m; s – a pitch between the pipes, m; h – depth of pipe occurrence, m.

The heat transfer coefficient α_2 is determined according to the algorithm given for calculating the heat transfer coefficient α_1, and the characteristic dimension is not a liquid filling height h_{load} and the diameter of the cooling tube d_t, and the temperature of a circulating refrigerant is taken as reference temperature.

From the heat balance equation (1) we obtain the expression for the surface area of the cooling tubes:

$$S_t = \frac{k_1 \cdot S_{bot} \cdot \Delta T_1 \cdot \Delta\tau + Q_{ph.t.}}{2 \cdot \Delta T_2 \cdot \Delta\tau} \cdot \left(\frac{2}{\alpha_2} + \frac{d_t}{\lambda_s} \ln\left[\frac{2 \cdot s}{\pi \cdot d_t} \mathrm{sh}\left(2\pi \frac{\mathrm{h} + \lambda_s/\alpha_1}{s}\right)\right]\right) \tag{10}$$

The ratio to determine the diameter of the pipe is the following:

$$d_t = \frac{S_t}{\pi \cdot l}, \tag{11}$$

where the tube length *l* is determined by the formula

$$l = 2 \cdot \left\{ \left(\frac{N}{2} - 1\right) \cdot s + \sum_{i=1}^{N/2} 2\sqrt{i \cdot s \cdot D_{res} - (i \cdot s)^2} \right\} \tag{12}$$

Here, D_{res} −the outer diameter of the vessel, m; N −the number of turns of the coil equal to

$$N = \frac{D_{res} + 2}{d_t + s} + 1 \tag{13}$$

Substituting the expressions (2) – (5) in equation (10), we will check the resulting equation using the parameters of the experimental setup and media used in the experiment. The thermal physic properties of heat transfer agents are shown in Table 2.

Table 2. The thermal physic properties of heat transfer agents [13; 15].

Parameter	Hot heat transfer agent	Cold heat transfer agent
Determining temperature, ° C	33	−7.0
Wall temperature, ° C	36	−6.3
Kinematic Viscosity, m^2/s	$0.776 \cdot 10^{-6}$	$0.510 \cdot 10^{-6}$
Thermal volume expansion coefficient, K^{-1}	$3.34 \cdot 10^{-4}$	$6.20 \cdot 10^{-4}$
Thermal conductivity coefficient, W/(m·K)	0.62	0.33
Prandtl number at the determining temperature, dimensionless	5.30	468.18
Prandtl number at the wall temperature, dimensionless	5.12	435.26

The tank diameter is 0.52 m, the wall thickness is 3 mm. The tank is made of steel with a coefficient of thermal conductivity of 52 W/(m·K).

Having based on the graphs of temperature fields and the amount of soil porosity, equal to 0.25, there has been determined the volume of liquid transited from liquid to solid. This heat of phase transition was 78.70 kJ.

The heat transfer coefficient from the tank into the soil is 7.46 W/(m^2·K) and the amount of heat transferred for 1 hour is 176.12 kJ. The heat transfer coefficient from the cooling pipes into the soil was 32.71 W/(m^2·K).

The actual area of the coil used in the experiment is defined by the formula

$$S_t = \pi \cdot d_t \cdot l \tag{14}$$

Thus, the coil area value obtained by the heat balance equation coincides with the actual error within 1%.

5. Conclusion

The comparison of the calculated values of heat exchange surface area, obtained on the basis of the experimental data to the real geometrical dimensions of the coil circuit indicate the possibility of using the proposed method of calculation for horizontal thermal stabilization systems with forced circulation of a heat transfer agent for temperature stabilization tasks of soil bases under the tank with the heat transfer agent in the conditions of the experiments.

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