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PERMAFROST ENGINEERING

COOLING DEVICES DESIGNED TO RESTORE THE LOADING CAPACITY OF SOILS UNDER EXISTING BUILDINGS AND STRUCTURES

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A new device for temperature stabilization of frozen soils is suggested. The advantage of the proposed system is the ability to install the evaporative part of the system under the construction and operating facilities. The difference from the analogous systems is the ability to repair and replace individual evaporator pipes without dismantling the entire device while maintaining its high freezing capacity. To assess the efficiency of the proposed system, an analytical mathematical model of its functioning has been developed. The modeling of the functioning of the seasonal cooling device for the climatic conditions of the Arctic cities of Varandey, Salekhard, and Igarka has been carried out. It is shown that this device can always freeze the soil under emergency buildings and structures.

Keywords: *permafrost, soil, seasonal cooling unit, condenser, pipeline, evaporator unit, condenser, pipeline, evaporator.*

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INTRODUCTION

Currently, the trend towards increasing permafrost thawing depth continues. Cyclic warming also plays an important role in this process. Warming is evidenced by a rapid reduction in the Arctic ice cover, an increase in the thickness of the seasonally thawed permafrost layer, and a decrease in the duration of snow cover and other indicators [*Roshydromet, 2020*].

However, we should not forget about thermal anomalies of the urban climate, which have a noticeable impact on both the economy and ecology of the city [*Esau et al., 2019*]. In cities, heat flows lead to an increase in the depth of seasonal thawing, which, in turn, creates a threat to infrastructure facilities – the bearing capacity of foundations decreases [*Roshydromet, 2008*]. Thus, the problem arises of preserving the soils underlying buildings and structures in a frozen state. At the moment, one of the most efficient means of cooling and freezing soils under permafrost conditions is seasonal cooling devices (**SCD**), a detailed description and principle of operation of which are given in [*Dolgikh et al., 2008; Anikin et al., 2011; Anikin, Spasennikova, 2012*]. *Earlier,* numerical modeling of the SCD operation was carried out to assess the efficiency of their use in certain geocryological conditions in order to choose the most optimal version of the system [*Dolgikh et al., 2013, 2014, 2015; Anikin et al., 2017, 2018; Gorelik, Khabitov, 2019; Gorelik et al., 2019*]. This work presents a new system for temperature stabilization of frozen soils, patented by the authors [*Patent..., 2020*]. The main advantage of the proposed SCD model is the ability to install evaporators under buildings (structures) under construction and in operation on frozen soils, as well as the ability to repair and replace individual evaporator pipes without dismantling the entire device, while maintaining its high freezing capacity. To assess the effectiveness of the proposed system, an analytical model of its functioning has been developed.

PRINCIPLE OF OPERATION OF THE COOLING DEVICE

The device for temperature stabilization (Fig. 1) is a condenser installed on a tower; the coolant supply pipeline is made in the form of a vertical pipe that turns into a horizontal one, and then an inclined pipeline removes the coolant. The evaporators located at the base of the structure below the ground surface are connected to an inclined pipeline. The supply pipeline and coolant discharge pipeline form a circuit closed through the condenser.

From the condenser, the coolant liquid (carbon dioxide, ammonia or other refrigerant) flows through supply pipes into an inclined pipeline, from which it flows into the evaporators. The refrigerant (coolant) that has taken up the heat in the form of gas bubbles moves upward under the influence of the Archimedes force and enters the coolant removal pipeline, then the two-phase coolant mixture enters the condenser.

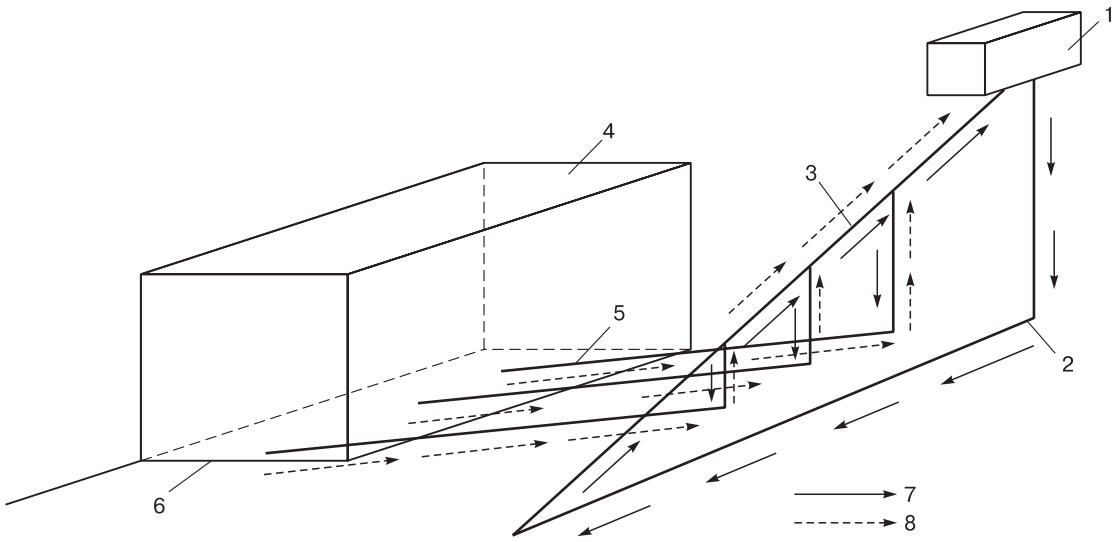

Fig. 1. General view of the installation designed to strengthen the foundations under existing structures built on permafrost.

1 – condenser; 2 – coolant supply pipeline; 3 – coolant outlet pipeline; 4 – building; 5 – evaporator; 6 – ground level; 7 – fluid flow; 8 – gas flow.

The gaseous coolant is condensed in the condenser, after which the liquid phase of the refrigerant enters the evaporators, in which it evaporates cooling the surrounding soil. The cycle is repeated many times.

A device for temperature stabilization of the foundations of structures [*Patent..., 2020*] can be used in the construction of residential and industrial buildings on permafrost and also makes it possible to strengthen the foundations of buildings and structures that are in emergency condition.

To assess the efficiency of the system, consider the developed mathematical model.

MATHEMATICAL MODEL OF THE SYSTEM PERFORMANCE

Let us consider the pipe with radius b and length L, surrounded by frozen soil shaped as a cylinder with radius R_0 (Fig. 2).

To a first approximation, we assume that the freezing front is motionless; then, the temperature of the soil inside the frozen cylinder is given by the equation:

$$\frac{1}{r}\frac{d\left(rdt\left(r\right)/dr\right)}{dr}=0. \quad (1)$$

Here, t is the temperature in degrees Celsius, r is the radial coordinate of the cylindrical coordinate system (the distance from the center of the evaporator pipe to the ground point in question). The solution to this equation is written in the following form:

$$t(r) = C \ln (r) + C_1, \quad (2)$$

where C and C_1 are constants that need to be determined.

The boundary conditions for the problem under consideration are written in the form:

$$t\,(b) = t_{ev},\ t\,(R_0) = t_{bf}. \quad (3)$$

Here, b is the radius of the evaporator pipe; R_0 is the radius of the freezing boundary; $t(b)$ is the tem-

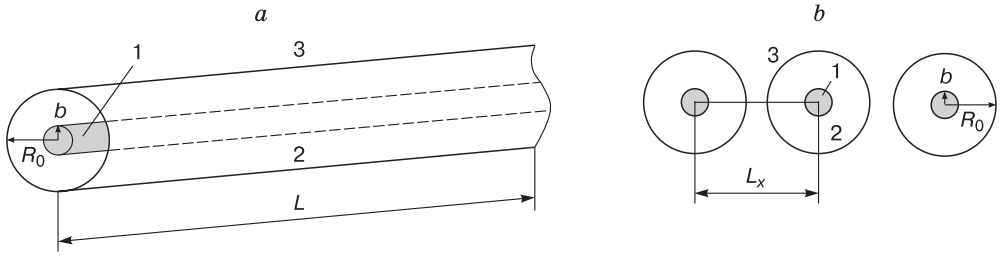

Fig. 2. Evaporator pipe design: (*a*) side view, (*b*) front view.

1 – evaporator, 2 – frozen soil, 3 – unfrozen soil; L_x – distance between the pipes of the evaporation system.

perature at $r = b$; $t(R_0)$ is the temperature at $r = R_0$; t_{ev} is the evaporator temperature; and t_{bf} is the phase transition temperature. From Eqs. (2) and (3) we obtain:

$$t_{bf} - t_{ev} = C \ln\left(\frac{R_0}{b}\right) \rightarrow C = \frac{t_{bf} - t_{ev}}{\ln\left(R_0/b\right)}.$$

The heat flux (dU), which is supplied to the evaporator pipe element of length (dL), in absolute value is equal to:

$$dU = \lambda \frac{\partial t}{\partial r} 2\pi r dL = 2\pi\lambda \frac{\left(t_{bf} - t_{ev}\right)}{\ln\left(R_0/b\right)} dL, \quad (4)$$

where λ is the thermal conductivity coefficient of frozen soil. The total thermal power of the cooling system (U_{tot}) is limited by the efficiency of the condenser part ($\alpha S\eta$) and is equal to:

$$U_{tot} = \alpha S\eta\ (t_{con} - t_a), \quad (5)$$

where α is the heat transfer coefficient of the condenser surface; S is the surface area of the condenser; η is the efficiency coefficient of the condenser fins; t_{con} is the temperature of the condenser; and t_a is the temperature of the atmosphere. As follows from the work [*Anikin, Spasennikova, 2014*], the temperatures of the condenser and evaporateor are related to each other by the relation:

$$t_{ev} = t_{con} + \frac{\rho_L g H}{\left(dP/dt\right)}, \quad (6)$$

where g is the acceleration of gravity; H is the height of the condenser rising above the evaporator; ρ_L is the density of the liquid refrigerant; and P is the saturated vapor pressure of the refrigerant at temperature t. In turn, H is equal to:

$$H = H_0 + L \sin\varphi, \quad (7)$$

where H_0 is the height of the condenser above the ground surface, L is the distance from the ground surface to the evaporator point under consideration, and φ is the angle between the evaporator pipe and the ground surface. Taking into account Eqs. (5)–(7) we obtain:

$$t_{ev} = t_a + \frac{U_{tot}}{\alpha S\eta} + \frac{\rho_L g\left(H_0 + L\sin\varphi\right)}{dP/dt}. \quad (8)$$

Substituting (8) into (4), we get:

$$dU = 2\pi\lambda \frac{\left(t_{bf} - t_a - \dfrac{U_{tot}}{\alpha S\eta} - \dfrac{\rho_L g\left(H_0 + L\sin\varphi\right)}{dP/dt}\right)}{\ln\left(R_0/b\right)} dL.$$

Carrying out integration over L, we obtain:

$$U\frac{\ln\left(R_0/b\right)}{2\pi\lambda} =$$

$$= \left(t_{bf} - t_a - \frac{U_{tot}}{\alpha S\eta} - \frac{\rho_L g H_0}{dP/dt}\right) L_0 - \frac{\rho_L g\left(L_0^2 \sin\varphi\right)}{2\,dP/dt}.$$

Or, which is the same:

$$U\frac{\ln\left(R_0/b\right)}{2\pi\lambda} = \left(t_{bf} - t_a - \frac{U_{tot}}{\alpha S\eta} - \frac{\rho_L g\bar{H}}{dP/dt}\right) L_0, \quad (9)$$

$$\bar{H} = H_0 + 0.5 L_0 \sin\varphi,$$

where L_0 is the length of the evaporator pipe (Fig. 1).

By multiplying both sides of Eq. (9) by the number of evaporator pipes (N), we get:

$$U_{tot}\frac{\ln\left(R_0/b\right)}{2\pi\lambda} = \left(t_{bf} - t_a - \frac{U_{tot}}{\alpha S\eta} - \frac{\rho_L g\bar{H}}{dP/dt}\right) L_{tot}. \quad (10)$$

Here, it is taken into account that the following relations are satisfied:

$$U_{tot} = UN,\ L_{tot} = LN.$$

From Eq. (10), we find the value of the total thermal power (U_{tot}):

$$U_{tot} = \left(t_{bf} - t_a - \frac{\rho_L g\bar{H}}{dP/dt}\right) \Bigg/ \left(\frac{1}{\alpha S\eta} + \frac{\ln\left(R_0/b\right)}{2\pi\lambda L_{tot}}\right). \quad (11)$$

Now let us consider the integral solution. The amount of heat from the phase transition released by the soil, when a cylinder of radius R_0 and length L_{tot} freezes, is written as:

$$Q_{bf} = \sigma\pi R_0^2 L_{tot}, \quad \sigma = \sigma_0\gamma\left(w - w_0\right),$$

where Q_{bf} is the heat of phase transition, J; σ_0 is the specific heat of ice melting, J/kg; γ is the density of the rock skeleton, kg/m^3; w is the total moisture content of the rock; w_0 is the content of unfrozen water; and σ is the heat of freezing of one cubic meter of soil.

The heat Q_t that leaves the system due to temperature changes is equal to:

$$Q_t = \int_b^{R_0} \left(c_1\left(t_0 - t_{bf}\right) + c_2\left(t_{bf} - t\left(r\right)\right)\right) L_{tot} 2\pi r dr. \quad (12)$$

The solution to Eq. (1) can be written as:

$$t\left(r\right) = \frac{t_{bf} - t_{ev}}{\ln\left(R_0/b\right)} \ln\left(\frac{r}{b}\right) + t_{ev}, \quad (13)$$

where $t(r)$ is the temperature at a distance r from the evaporator pipe, °C; c_1 is the volumetric heat capacity of thawed soil, J/(m$^3\cdot$°C); c_2 is the volumetric heat capacity of frozen soil; J/(m$^3\cdot$°C); and t_0 is the initial soil temperature, °C.

Substituting (13) into (12), we get:

$$Q_t = \left(c_1\left(t_0 - t_{bf}\right) + c_2\left(t_{bf} - t_{ev}\right)\right) L_{tot}\pi R_0^2 -$$

$$- c_2 L_{tot} \frac{t_{bf} - t_{ev}}{\ln\left(R_0/b\right)} \int_b^{R_0} \ln\left(\frac{r}{b}\right) 2\pi r dr.$$

Thus, the energy balance equation will be written as:

$$\int_0^{\tau} U_{tot}\left(\tau'\right) d\tau' = Q_t + Q_{bf}, \quad (14)$$

where τ is time, days.

Differentiating both sides of Eq. (14) with respect to τ, we obtain:

$$U_{\text{tot}} = \frac{dR_0}{d\tau}\left(\frac{\partial\left(Q_t + Q_{\text{bf}}\right)}{\partial R_0}\right). \quad (15)$$

Note that the solution to the integral below can be written as:

$$\int_b^{R_0} \ln\left(\frac{r}{b}\right) 2\pi r dr = 2\pi b^2 \int_1^{\frac{R_0}{b}} x\ln(x)dx = \\ = 2\pi b^2\left(F\left(\frac{R_0}{b}\right) - F(1)\right), \quad (16)$$

where $F(x)$ is a function that is given by the following expression:

$$F(x) = \frac{x^2}{2}\ln(x) - \frac{x^2}{4}. \quad (17)$$

Thus, the right side of Eq. (15), taking into account Eqs. (16) and (17), will be written as:

$$\frac{\partial\left(Q_t + Q_{\text{bf}}\right)}{\partial R_0} = 2\pi R_0 L_{\text{tot}}\left(\sigma + c_1\left(t_0 - t_{\text{bf}}\right)\right) + \\ + c_2 L_{\text{tot}} \frac{t_{\text{bf}} - t_{\text{ev}}}{\left(\ln\left(R_0/b\right)\right)^2} \frac{2\pi b^2\left(F\left(R_0/b\right) - F(1)\right)}{R_0}. \quad (18)$$

Note that in Eq. (18) the following substitution can be made:

$$2\pi b^2\left(F\left(\frac{R_0}{b}\right) - F(1)\right) = \pi R_0^2 \ln\left(\frac{R_0}{b}\right) - \pi\frac{R_0^2}{2} + \frac{\pi b^2}{2}.$$

Thus, we get:

$$\frac{\partial\left(Q_t + Q_{\text{bf}}\right)}{\partial R_0} = 2\pi R_0 L_{\text{tot}}\left(\sigma + c_1\left(t_0 - t_{\text{bf}}\right) + \right. \\ \left. + c_2\left(t_{\text{bf}} - t_{\text{ev}}\right)\frac{\left(\ln\left(R_0/b\right) - 0.5 + 0.5b^2/R_0^2\right)}{2\left(\ln\left(R_0/b\right)\right)^2}\right). \quad (19)$$

To assess the correctness of the resulting solution, it is necessary to prove the convergence of the right-hand side of Eq. (19) as $R_0 \to b$.

Assuming $R_0 = b + x$, we get:

$$\lim_{x\to 0} \frac{\left(\ln\left(R_0/b\right) - 0.5 + 0.5b^2/R_0^2\right)}{2\left(\ln\left(R_0/b\right)\right)^2} = \\ = \lim_{x\to 0} \frac{x - 0.5x^2 - 0.5 + 0.5\left(1 - 2x + 6x^2\right)}{2x^2} = \frac{2.5}{2}.$$

Thus, Eq. (19) converges to a final, positive value.

To simplify the obtained expressions, we introduce the function φ(x):

$$\varphi(x) = \frac{\ln x - 0.5 + 0.5/x^2}{\left(\ln x\right)^2}. \quad (20)$$

Then, from (11), (15), (19) and (20) we obtain the differential equation:

$$\left(t_{\text{bf}} - t_{\text{a}} - \frac{\rho_L g\bar{H}}{dP/dt}\right) \Big/ \left(\frac{1}{\alpha S\eta} + \frac{\ln\left(R_0/b\right)}{2\pi\lambda L_{\text{tot}}}\right) = \\ = \frac{dR_0}{d\tau} 2\pi R_0 L_{\text{tot}}\left(\sigma + c_1\left(t_0 - t_{\text{bf}}\right) + c_2\left(t_{\text{bf}} - t_{\text{ev}}\right)\varphi\left(\frac{R_0}{b}\right)\right).$$

Or, which is the same:

$$d\tau\left(t_{\text{bf}} - t_{\text{a}} - \frac{\rho_L g\bar{H}}{dP/dt}\right) = dR_0 \frac{2\pi R_0}{\lambda}\left(\frac{\lambda L_{\text{tot}}}{\alpha S\eta} + \frac{\ln\left(R_0/b\right)}{2\pi}\right) \times \\ \times\left(\sigma' + c_2\left(t_{\text{bf}} - t_{\text{ev}}\right)\varphi\left(\frac{R_0}{b}\right)\right), \quad (21)$$

where the value σ′ is given by the relation:

$$\sigma' = \sigma + c_1\left(t_0 - t_{\text{bf}}\right).$$

Let us consider the case when the condition is met:

$$c_2\left(t_{\text{bf}} - t_{\text{ev}}\right)\varphi\left(\frac{R_0}{b}\right) \ll \sigma', \quad \alpha = \text{const}.$$

Then, Eq. (21) can be integrated explicitly:

$$\tau\left(t_{\text{bf}} - \bar{t}_{\text{a}}(\tau) - \frac{\rho_L g\bar{H}}{dP/dt}\right) = \frac{\pi\left(R_0^2 - b^2\right)}{\lambda} A\sigma' + \\ + \frac{b^2}{\lambda}\left(\left(\frac{R_0^2}{2b^2}\ln\left(\frac{R_0}{b}\right) - \frac{R_0^2}{4b^2}\right) + 0.25\right)\sigma'. \quad (22)$$

Here, the quantities $\bar{t}_{\text{a}}$ and A are given by the following relations:

$$\bar{t}_{\text{a}}(\tau) = \frac{1}{\tau}\int_0^{\tau} t_{\text{a}}(\tau')d\tau', \quad A = \frac{\lambda L_{\text{tot}}}{\alpha S\eta}.$$

Thus, an analytical solution has been obtained that can be used to assess the efficiency of the system presented in the work.

ASSESSMENT OF THE SYSTEM EFFICIENCY

Let us consider soil freezing under the impact of the described cooling device for different climatic zones. For this purpose, we use meteorological parameters obtained by averaging archival data from weather stations in the Arctic cities of Varandey, Salekhard, and Igarka (Table 1) [*https://rp5.ru*].

Table 1. **Mean monthly air temperatures (t_a) and wind speeds (v_a) in Arctic cities**

Month	Weather station					
	Varandey		Salekhard		Igarka	
	t_a, °C	v_a, m/s	t_a, °C	v_a, m/s	t_a, °C	v_a, m/s
January	–14.7	6.9	–22.9	2.2	–26.1	3.1
February	–18.9	6.3	–19.2	2.2	–18.2	2.6
March	–13.0	6.2	–12.7	2.8	–14.6	2.9
April	–7.1	5.7	–5.5	3.2	–1.9	3.2
May	–1.5	5.6	1.1	3.4	3.9	3.4
June	6.1	5.6	11.6	3.5	11.4	3.1
July	10.8	5.8	16.0	2.9	15.8	2.8
August	9.2	6.1	11.5	2.9	11.2	2.8
September	6.5	5.7	6.3	2.9	7.1	3.1
October	1.5	6.9	–2.5	2.7	–4.2	3.3
November	–7.8	5.7	–13.4	2.5	–19.2	2.8
December	–21.3	2.8	–17.6	2.1	–24.4	3.2

It is worth noting that the analysis of the efficiency of the proposed installation will be carried out for a number of variable parameters, such as air temperature, wind speed, thermal conductivity of frozen soil, and the total length of the evaporator pipes. Of course, there may be significantly more parameters, but those that have the greatest impact on the efficiency of the system have been selected.

The dynamics of changes in air temperature and wind speed are different for each area for which the operation of the proposed system will be calculated. The calculation of the operating time of the installation for each of them, except for Varandey, is carried out from the beginning of October, as the first month with negative temperatures. For Varandey, calculations begin in November.

Table 2. **The dependence of freezing radius (R_0) on time (τ) at different lengths of the evaporative system (L_{tot}) and the thermal conductivity of frozen soil λ = 2 W/(m·°C) for the conditions of Salekhard**

τ, days	R_0, m		
	L_{tot} = 300	L_{tot} = 1000	L_{tot} = 3000
0	0.016	0.016	0.016
20	0.232	0.186	0.129
40	0.422	0.347	0.247
60	0.616	0.514	0.372
80	0.790	0.664	0.486
100	0.943	0.797	0.587
120	1.089	0.924	0.684
140	1.199	1.020	0.758
160	1.281	1.092	0.813
180	1.341	1.145	0.853
200	1.369	1.169	0.872

Table 3. **The dependence of freezing radius (R_0) on time (τ) at different lengths of the evaporative system (L_{tot}) and the thermal conductivity of frozen soil λ = 2 W/(m·°C) for the conditions of Varandey**

τ, days	R_0, m		
	L_{tot} = 300	L_{tot} = 1000	L_{tot} = 3000
0	0.016	0.016	0.016
20	0.199	0.172	0.130
40	0.354	0.312	0.243
60	0.511	0.456	0.360
80	0.660	0.592	0.472
100	0.791	0.713	0.573
120	0.918	0.830	0.670
140	1.050	0.952	0.772
160	1.153	1.047	0.852
180	1.227	1.116	0.910
200	1.271	1.157	0.944

The output parameter that will be evaluated and by which a conclusion will be made about the efficiency of the system is the radius of the frozen soil around the evaporator pipe. The criterion for the efficiency of the proposed system will be considered to be the radius of the frozen soil halo $R_0(\tau)$, at which the freezing halos from two parallel evaporator pipes will merge together, that is, the condition will be met:

$$R_0(\tau) = \frac{L_x}{2},$$

where L_x is the distance between the pipes of the evaporation system (Fig. 2*b*). It is worth clarifying that during all calculations we assume that γ = = 1600 kg/m^3, $w_0 = 0$, $w = 0.2$, $c_1 = 2.8 \cdot 10^6$ J/(kg·°C), $c_2 = 1.8 \cdot 10^6$ J/(kg·°C).

Table 4. **The dependence of freezing radius (R_0) on time (τ) at different lengths of the evaporative system (L_{tot}) and the thermal conductivity of frozen soil λ = 2 W/(m·°C) for the conditions of Igarka**

τ, days	R_0, m		
	L_{tot} = 300	L_{tot} = 1000	L_{tot} = 3000
0	0.016	0.016	0.016
20	0.294	0.243	0.173
40	0.515	0.434	0.318
60	0.740	0.631	0.469
80	0.939	0.806	0.604
100	1.102	0.950	0.716
120	1.245	1.077	0.816
140	1.340	1.161	0.882
160	1.415	1.228	0.934
180	1.478	1.283	0.978
200	1.491	1.295	0.987

The heat transfer coefficient between the condenser and the atmosphere, in accordance with the work [*Royzen, Dulkin, 1977*], is given by the following expression:

$$\alpha(t) = 0.105\frac{\lambda_a(t)}{s}\left(\frac{d}{s}\right)^{-0.54}\left(\frac{h}{s}\right)^{-0.14}\left(\frac{vs}{\nu_a(t)}\right)^{0.72},$$

where s is the distance between the fins of the capacitor, m; d is the diameter of condenser pipes, m; h is the capacitor fin length, m; $\lambda_a(t)$ is the thermal conductivity of air, W/(m·°C); $\nu_a(t)$ is the kinematic viscosity of air, Pa·s; v is wind speed, m/s.

For the installation presented in the work, the characteristics of the capacitor have the following values: d = 32 mm, s = 7 mm, h = 34 mm. The viscosity and thermal conductivity of air depend on the temperature of the atmosphere and are set according to reference data [*Babichev et al., 1991*].

Solving Eq. (22) for the meteorological parameters of Salekhard, we obtain the following distributions of the radius of soil freezing depending on time (Table 2).

Solving Eq. (22) for the meteorological parameters of Varandey, we obtain the following distributions of the radius of soil freezing depending on time (Table 3).

Solving Eq. (22) for the meteorological parameters of Igarka, we obtain the following distributions of the radius of soil freezing depending on time (Table 4).

For a better presentation of the data, Figs. 3*a*–3*c* show a comparison of the analytical solution (22) with the exact differential solution (21) for three Arctic cities.

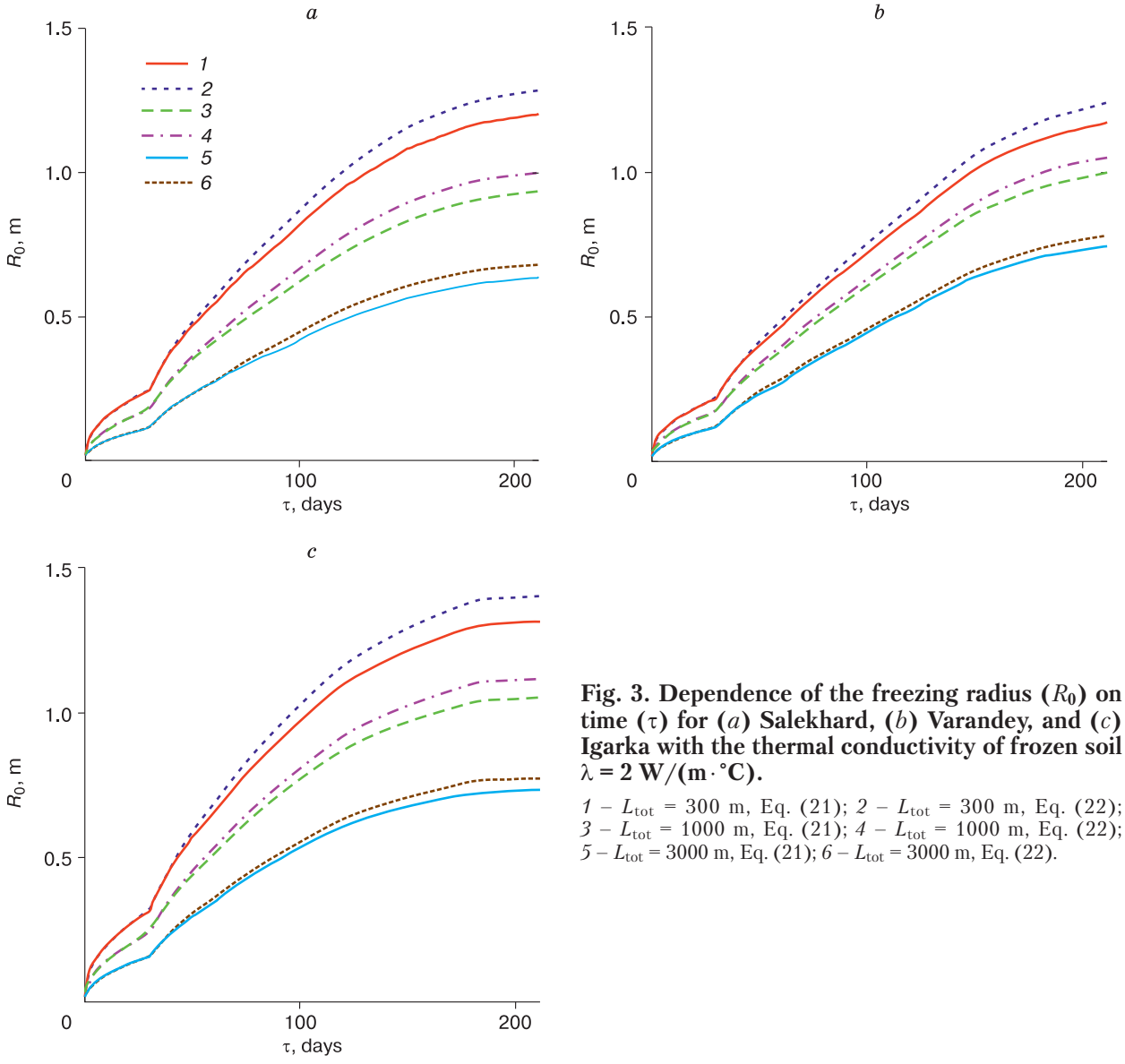

Fig. 3. Dependence of the freezing radius (R_0) on time (τ) for (*a*) Salekhard, (*b*) Varandey, and (*c*) Igarka with the thermal conductivity of frozen soil λ = 2 W/(m·°C).

1 – L_{tot} = 300 m, Eq. (21); *2* – L_{tot} = 300 m, Eq. (22); *3* – L_{tot} = 1000 m, Eq. (21); *4* – L_{tot} = 1000 m, Eq. (22); *5* – L_{tot} = 3000 m, Eq. (21); *6* – L_{tot} = 3000 m, Eq. (22).

Thus, it is evident that the resulting analytical solution (22) differs by less than 7% from the exact differential solution (21) and can be used to assess the efficiency of the functioning of temperature stabilization systems for frozen soils.

According to the data obtained, it is clear that if the distance between the pipes of the evaporation system is 1 m, then the entire soil will freeze in 100 days, that is, in half the time of the winter season, since the freezing radius during this time will, as a rule, be more than 0.5 m.

To assess the practical significance, consider the volume of frozen soil within a 1-m distance between the pipes of the evaporation system:

$$V_{\text{tot}} = \pi R_0^2 L_0 N = \pi R_0^2 L_{\text{tot}}.$$

Thus, with a fin area of the condenser part of 100 m^2, for 100 days of operation of the proposed temperature stabilization system with a total length of the evaporation part of 3000 m, for Salekhard, R_0 = 0.587 m, V_{tot} = 3246 m^3; for Varandey, R_0 = 0.573 m, V_{tot} = 3093 m^3; and for Igarka, R_0 = 0.716 m, V_{tot} = 4829 m^3.

CONCLUSIONS

(1) The work presents a new device for temperature stabilization of frozen soils, the key advantage of which is the possibility to install the evaporation part of the system during construction, as well as during operation of the facilities.

(2) The advantage of the presented system is the possibility to repair and replace individual evaporator pipes without dismantling the entire device while maintaining its high freezing capacity.

(3) The work presents an analytical mathematical model of the functioning of the described system. The efficiency of the proposed system was also assessed by simulating the functioning of the seasonal cooling device of various designs for the climatic conditions of the Arctic cities of Varandey, Salekhard, and Igarka.

(4) It is shown that it is always possible to freeze a large area of soil under emergency buildings and structures by installing the proposed system.

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