Thermal impact of buried reservoirs with industrial waste of the fuel and energy complex on frozen soils

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Abstract. The oil and gas industry has been intensively developing in the far north of the Russian Federation. Underground tanks are repositories of waste from processed petroleum products, liquefied gas, condensate, process water, and other waste from the fuel and energy complex. High-quality underground disposal of industrial waste can eliminate leakage of chemicals into the soil and reduce the thermal effect on frozen soil. The article presents an algorithm for calculating the thermal effect of industrial "hot" waste of the fuel and energy industry on frozen soil. Heat fluxes from a 20,000 m³ tank are estimated, an area of soil thawing is calculated. An engineering solution was developed to reduce / eliminate this effect.

1. Introduction
One of the most important tasks of the economic and social development of territories is the use of the underground space of the permafrost zone for various economic needs of the fuel and energy industry. Therefore, the environmental issue of the efficient use of permafrost soils is very acute [5].

Underground tanks are repositories of waste from processed petroleum products, liquefied gas, condensate, process water, agricultural products, radioactive waste, etc. The disposal of industrial waste or the storage of other petroleum products is regulated by laws.

During the operation of underground tanks, there is a thermal effect of the product on frozen soils. The continuity of the moss cover is disturbed in the permafrost zone, which leads to the destruction of the chemical composition of soils, erosion and disruption of the natural balance of the ecosystem. Unfortunately, many manufacturers are forced to put up with the lack of effective methods of operating the fuel and energy industry in special climatic conditions. They pay substantial fines.

High-quality underground disposal of industrial waste will reduce the thermal effect on frozen soil, and reduce unforeseen production costs (fines). The negative temperature of soils will have a frosting effect on the waste, which can reduce their activity [5].

2. Problem statement
To study the thermal effect of the “hot” reservoir on frozen ground, we took a model of a vertical cylindrical concrete underground reservoir with a capacity of 20,000 m³, with known characteristics [6, 7] (table 1).
Table 1. Characteristics of the vertical cylindrical concrete underground tank and frozen soil

| Characteristic | Value |
|---------------|-------|
| V = 20 000 m$^3$ | tank volume |
| H = 9 m | height |
| D = 54 m | diameter |
| $\Delta_w = 0,2$m, $\delta_b = 0,3$m, $\delta_c = 0,2$m | thickness of the wall, bottom, cover, respectively. |
| Tank material - concrete |  
| $\rho = 2300$ kg/m$^3$ | concrete density |
| $\lambda_{concrete} = 1,35$ W/(m·°C) | concrete heat capacity |
| $C_0 = 840$ J/(kg·°C) | concrete heat capacity |

The tank was buried in permafrost soil. The height from the tank roof to the surface is 1.5 m. The soil is a homogeneous stationary medium. Density, heat capacity and thermal diffusivity depend on temperature changes [2]. The thermophysical characteristics of the soil in which the tank was installed are presented in table 2.

Table 2. Thermophysical soil characteristics

| Characteristic | Value |
|---------------|-------|
| $t_{gr} = -7$ °C | soil temperature |
| $\lambda_{gr} = 3$ W/(m·°C) | soil thermal conductivity |
| $C_{gr} = 920$ J/(kg·°C) | soil heat capacity |
| $\rho_{gr} = 2083$ kg/m$^3$ | soil density |

Water with dissolved mechanical impurities was taken under the buried product. The initial temperature is 45 °C.

3. Calculation method
Since the tank, as a real heat source, has finite dimensions and acts for a finite period of time, when solving the problem, the fundamental solution to the heat equation can be used [3]. The tank was considered as a point source; and the time was divided into many infinite small intervals. From the heat source (reservoir) into the surrounding soil, the heat diverged simultaneously in three different directions: x, y, z. The process of cooling was modeled in the C ++ programming language.

To determine an area of soil thawing, it was decided to use the following dependence [2]:

$$T(r, t) = \frac{Q}{4\pi \lambda r} erfc \left( \frac{r}{\sqrt{4a \tau}} \right) \quad (1)$$

where $Q$ – variable heat flux, which is formed from storage products in the tank, [W];
$\lambda$ - soil thermal conductivity coefficient, [W / (m·°C)];
$a$ - soil thermal diffusivity coefficient [m$^2$/s]; $r$ - the distance from the heat source (tank) to the observation point, [m]; $\tau$ is time, [s].

The thermal diffusivity was determined by formula:

$$a = \frac{\lambda_g}{c_g \rho_g} \quad (2)$$

The distance from the tank to the heating point was determined by formula:

$$r^2 = x^2 + y^2 + z^2 \quad (3)$$
Since the heat from waste will be transferred to the soil, the soil will be cooled. The temperature of the buried product will decrease. Changes in the temperature of the tank can be determined by formula [1]:

\[ T = T_0 + (T_H - T_0)e^{-\frac{t}{k_t}} \]  

(4)

where \( T_0 \) - ambient temperature, [K];
\( T_I \) - initial temperature of the buried product, [K];
\( \tau \) - standing time, [sec];
\( k_t \) - dimensionless heat transfer coefficient.

Expressing \( \tau \) from this formula, we can determine the time during which the coolant is cooled to its ambient temperature.

Dimensionless heat transfer coefficient \( k_t' \) can be calculated by formula [1, 5, 8]:

\[ k_t' = \frac{V_0 \cdot \rho \cdot C + m_0 \cdot C_0}{k_t \cdot S} \]  

(5)

where \( V_0 \) - volume of the buried product, [m³];
\( \rho \) - density of the buried product, [k / m³];
\( C \) - heat capacity of the buried coolant product, [J / (kg · ºC)];
\( m_0 \) - mass of the empty concrete tank, [kg];
\( C_0 \) - heat capacity of concrete, [J / (kg · ºC)];
\( k_t \) - heat transfer coefficient from the surface of the tank to the surrounding soil, [W / (m · ºC)];
\( S \) - total surface area of the tank, [m²].

The dimensionless heat transfer coefficient (5) is an expression similar to the well-known formula of V.G. Shukhov for cooling the tank [8].

In formula (5), the heat transfer coefficient \( k_t \) is determined by complex equations that take into account heat transfer between the individual parts of the tank (bottom, roof, walls) and the liquid in the tank [8].

Under production conditions, it is desirable to have simpler equations or nomograms which can calculate the probable temperature drop with a variable flow rate of the disposal product and subsequent cooling of the tank [8].

The total heat transfer coefficient is determined by formula [1]:

\[ k_t = \frac{k_1 S_1 + k_2 S_2 + k_3 S_3}{S} \]  

(6)

where \( k_1, k_3 \) - heat transfer coefficient through the bottom, the tank roof, respectively, W/m² · deg;
\( S_1, S_3 \) - tank bottom area, m²;
\( k_2 \) - heat transfer coefficient through the side wall of the tank, W/m² · deg;
\( S_2 \) - tank wall area, m²;
\( S \) - total surface area of the tank, m².

To calculate the coefficient of heat transfer through the bottom, we use the formula [1, 5, 8]

\[ k_1 = \frac{1}{\alpha_{bd} + \frac{\delta_i \cdot \lambda_i + \pi \cdot \delta_{concrete} \cdot \lambda_{concrete}}{\pi \cdot g}} \]  

(7)

where \( \delta_i, \lambda_i \) - thickness and thermal conductivity of the concrete wall of the tank bottom, insulation, etc .;
\( \alpha_{bd} \) - coefficient of heat transfer from the buried product to the inner wall of the tank, W/m² · deg;
\( \lambda_s \) - soil thermal conductivity coefficient, W / m² · deg;
\( \delta_c \) - thickness of the concrete wall of the tank, m.
The heat transfer coefficient $\alpha_{1b}$ is determined by the similarity method through dimensionless quantities. The mechanism of heat transfer is free convection [3, 5, 8]:

$$\alpha_{1b} = \frac{1}{2} \cdot \frac{\lambda_{waste}}{D_{res}} \cdot (Gr \cdot Pr)^{0.25}_{waste} \cdot \left( \frac{Pr_{waste}}{Pr_{bottom \ walls}} \right)^{0.25}$$

(8)

The dimensionless Grashof’s numbers $Gr$ and Prandtl’s numbers $Pr$ are calculated according to the generally accepted dependencies. The temperature correction coefficient $\left( \frac{Pr_{waste}}{Pr_{bottom \ walls}} \right)_{0,25}$ is at the average temperature of the buried product $Pr_{waste}$, and the temperature of the tank bottom wall $Pr_{bottom \ walls}$. The temperature of the inner wall is based on physical considerations. At the end of the calculation, an adequacy of the temperature of the inner wall is checked. The calculation error is 3%.

The heat transfer coefficient through the wall $k_2$ can be determined by formula

$$k_2 = \frac{1}{\alpha_{1st \ concrete}} \cdot a_{1w}$$

(9)

where $\alpha_{1w}$ - heat transfer coefficient from the buried product to the inner vertical wall of the tank, $W/m^2 \cdot deg$.

This coefficient can be found by formula in (8). The mechanism of heat transfer is also free convection [1].

$$\alpha_{1w} = \frac{1}{2} \cdot \frac{\lambda_{waste}}{H} \cdot (Gr \cdot Pr)^{0.25}_{waste} \cdot \left( \frac{Pr_{waste}}{Pr_{bottom \ walls}} \right)^{0.25}$$

(10)

The coefficient of heat transfer from the coolant to frozen soil through the roof $k_3$ was calculated by formula:

$$k_3 = \frac{1}{\alpha_{1r} \cdot \frac{h_{gs}}{\lambda_{eq}} \cdot \frac{\delta_{roof}}{\lambda_{concrete}}}$$

(11)

where $\alpha_{1r}$ - heat transfer coefficient between the buried product and the free gas space to the tank roof, $W/m^2 \cdot deg$;

$h_{gs}$ - height of the gas space, m;

$\lambda_{eq}$ - equivalent gas space thermal conductivity, $W/m^2 \cdot deg$.

Formula (12) is used to determine the equivalent coefficient of thermal conductivity of the gas-air mixture $\lambda_{eq} = \lambda_c \cdot \varepsilon_x$,

$$\varepsilon_x = 0.18 \cdot (Gr \cdot Pr)^{0.25}$$

(13)

If $\varepsilon_x < 10^3$, $\varepsilon_x = 1$.

$$\lambda_c = \lambda_{gas} \cdot (1-C_i) + \lambda_{cp} \cdot C_i$$

(14)

The coefficient of thermal conductivity of the gas-air mixture with air humidity $C_i$ is determined in the gas space of the tank.

4. Results

By calculating the change in temperature of the buried product according to the above method, the dependence of temperature on the disposal time was obtained (see Figure 1).
Figure 1. The dependence of temperature of the buried product on disposal time

The graph shows that 20 days after, the temperature of the "hot" waste becomes equal to the temperature of the surrounding soil.

Figure 2 shows a graph of the temperature taken at various fixed distances from the tank center (the tank is presented as a point source). It can be seen that on the first day the soil warmed up, which is indicated by the peaks of the curves, and then the soil temperature gradually began to decrease. The closer the observation point to the reservoir, the higher the temperature of the soil is.

Figure 2. The dependence of soil temperature on disposal time at a fixed distance

Figure 3 shows that the temperature is maximum in the center of the tank and decreases monotonically with increasing distance r. The closer the moment of time t to the moment of the beginning of soil warming, the higher and narrower the peak of the curve T (r) is. Over time, heat gradually spreads in all directions, but if at any fixed point one can integrate (1) over the entire space, a value equal to Q can be obtained [3].
5. Engineering solution

To reduce the thermal effect of the tank with “hot” buried products on the soil, it was proposed to apply an insulation layer of calculated thickness that would reduce the thawing area [5].

For comparison, 4 insulation materials can be used:

- Mineral wool
- Foam glass
- Perlite
- Extruded polystyrene foam

Table 3 presents characteristics of the materials which affect the choice of insulation of the concrete tank in order to reduce the soil thawing effect.

| Characteristics                        | Mineral wool | Foam glass | Perlite | Extruded polystyrene foam |
|----------------------------------------|--------------|------------|---------|----------------------------|
| Heat conductivity coefficient, λ, W / (m·°C) | 0,035        | 0,075      | 0,05    | 0,04                        |
| Insulation layer thickness, δ, m      | 0,05         | 0,1        | 0,07    | 0,06                        |
| Cost, rub / m²                         | 50           | 2000       | 105     | 160                         |
| Cost of complete isolation, t,rub     | 310,59       | 121423,6   | 652,239 | 993,888                     |

Based on the results of the comparative analysis, one can conclude that the most advantageous insulating material is a 6 cm thick cushioning layer of extruded polystyrene. The standing thickness was selected so that the heat flux from the buried product causes minimal soil thawing.

Calculations of soil temperature in the presence of an additional layer between the soil and the wall of the concrete tank were made to justify the choice of an insulation material. The calculation results are presented in Figures 4 and 5.
Having analyzed the graphs, we can conclude that the selected material reduced the maximum temperature of soil heating by 6 times.

![Graph showing the dependence of soil temperature on the disposal time at a fixed point with insulation](image)

**Figure 4.** The dependence of soil temperature on the disposal time at a fixed point with insulation

![Graph showing the dependence of soil temperature on the distance to the observation point at a fixed time with insulation](image)

**Figure 5.** The dependence of soil temperature on the distance to the observation point at a fixed time with insulation

6. **Conclusion**

The thermal effect of the content of underground concrete tanks on frozen soil was studied. The method calculating the unsteady temperature field of the soil using the temperature of the cooled hot buried product was described. According to the calculations of the 20,000 m³ tank, the product cools down during 20 days, while frozen soil is thawed at a distance of 1.4 meters from the tank center. In areas of humid soils, the thermal influence can be dangerous, it can lead to the bulge of the tank to the surface, which can destroy the tank. The application of thermal insulation between soils and the tank wall can be an alternative way to reduce heat losses.
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