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Forecasting temperature behavior of soil in Gas field exploitation areas

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SUMMARY

The development of hydrate blocks in pipelines impedes the efficient exploitation of flowlines and may cause an emergency. It is necessary to determine the temperature behavior of soil to assess the potential risks of hydrate formation. For that purpose, we use an algorithm that allows us to obtain freezing depth data based on the current meteorological data and taking into account the onset of the negative temperatures period. The paper presents the calculations for the territory of the Eastern Oil- and Gas-bearing province of Ukraine. It has been established the standard depth of soil freezing at this territory. Long-term observations of air temperature at the meteorological station were used to forecast the depth of soil freezing. According to the reached results, the forecast advance period is 1 month.

Introduction. At the stage of transportation of natural gas, containing condensate impurities, from the well to the sites of complex preparation there is a danger of development of gas hydrates. The development of hydrate blocks in pipelines impedes the efficient exploitation of flowlines and may cause an emergency.

The development of methane gas hydrates occurs under conditions of high operating pressure in the pipeline and low temperature. At the same time, it remains a necessity to determine the temperature behavior of soil at the depth of the flowlines so that to assess the potential risks of hydrate formation (Poberezhny et al., 2017, 2018). Forecasting soil temperature behavior in gas fields areas will allow hydrate development inhibitors to be used efficiently. This, in turn, will reduce their toxic effects on the environment.

The use of the infrared thermography method (Prykhodko et al., 2018) is costly in this case. Therefore, they resort to analytical methods of soil temperature forecasting. In order to calculate the soil freezing depth and the temperature at the particular depth, V.V. Dokuchaev's formula is widely used (Gao et al., 2008, Trevoho et al., 2012, Yastrebov, 1972). It is based on the theory of the harmonic nature of soil temperature fluctuations. This formula takes into account only two parameters: the average annual air temperature and its amplitude. These parameters almost do not change from year to year for a specific territory. Therefore, the results of the calculations yield approximate and averaged data.

In our case, we need to use an algorithm that allows us to obtain freezing depth data based on the current meteorological data and taking into account the onset of the negative temperatures period.

Initial data. The initial data for the calculations is the climate information and the characteristics of the soil cover at the given area. It is known that the correlation coefficient between the air temperature and the topsoil temperature is close to 0.95 (Araghi et al., 2017). Therefore, the main parameter of the climatic information is the temperature of the surface air, which is taken as the basis for the calculation of soil temperature (Poberezhny and Kukhtar, 2017).

The paper presents the calculations for the territory of the Eastern Oil- and Gas-bearing province of Ukraine (Figure 1). In particular, the Mashivka-Shebelynka petroleum province in the south of Kharkiv region.

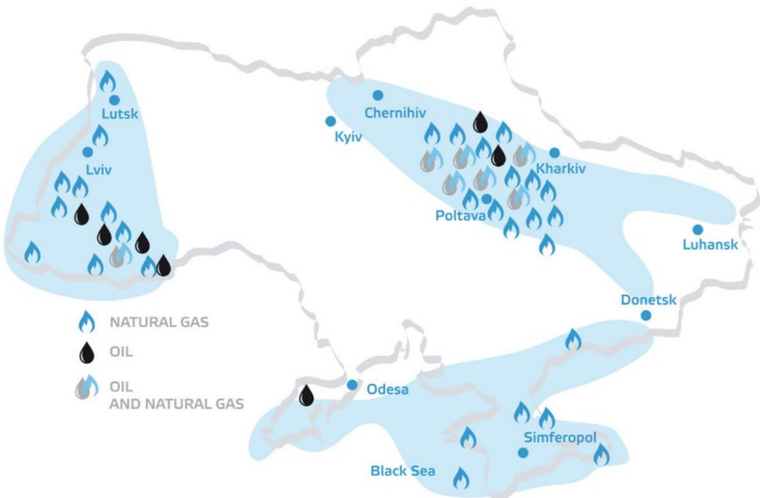

Figure 1 *Oil- and Gas-bearing provinces of Ukraine*

Climatic information

Today, temperature databases have high density and open access to meteorological data for different regions. The calculation of climatic parameters for the Eastern Oil- and Gas-bearing province was performed according to the algorithm (Svod pravyl, 2015). For this purpose, the data of observations of air temperature at the meteorological station in Izium (N 49° 11', E 37° 18'; 77 m above sea level) in Kharkiv region (Ukraine) for the period of 2008-2018 has been used.

The results of climatic information processing in a given territory are presented in Table 1.

***Table 1** Climatic parameters of the Eastern Oil- and Gas-bearing province*

Parameter	Denotement	Measurement Unit	Value
Average annual air temperature	T_y	*ºC*	9.3
Duration of the negative temperature period	t_{fm}	*days*	90
Mean air temperature of the negative temperature period	T_{fm}	*ºC*	-3.7
Duration of the positive temperature period	t_{hm}	*days*	270
Mean air temperature of the positive temperature period	T_{hm}	*ºC*	13.5

Soil characteristics

The main physical characteristics of the soil are its density ρ and humidity w. The density of frozen soil usually varies within 1.3 - 2.1 t/m^3. The higher ice content decreases the soil density. For frozen soil, total humidity w_{tot} is considered. That is, the amount of water in soil that is in a liquid (unfrozen water) and solid (ice) phases is taken into account. Moisture of unsalted, salty or peaty soil considering unfrozen water is determined from tables or by calculation (Svod pravyl, 2012).

The main quantitative characteristics of soil thermophysical properties are the coefficient of thermal conductivity λ, the volumetric heat capacity C and the coefficient of thermal conductivity α, which are determined experimentally. Thermophysical characteristics of soil cover depend on the ratio of a solid, liquid and gaseous component, texture and structural features of soil.

In the southern part of the Eastern Oil- and Gas-bearing province, southern black earths (middle loamy) are widespread. It is known that soil properties along the pipeline route may vary significantly. Therefore, the average values of the indicators, which are presented in Table 2, have been used for the calculations.

***Table 2** Characteristics of soil cover*

Parameter	Denotement	Measurement Unit	Value
Total soil moisture	w_{tot}	*u. f.*	0.27
Soil moisture due to unfrozen water	w_w	*u. f.*	0.09
Total soil density	ρ	*kg/m^3*	1860
Soil freezing temperature	T_{bf}	*ºC*	-0,2
The thermal conductivity coefficient of frozen soil	λ_f	*W/mºC*	1.54
the volumetric heat capacity of frozen soil	C_f	*J/m^{3}ºC*	2120000
The heat of ice melting	L_0	*J/kg*	334000

Calculation of soil freezing depth. The development of hydrates in the flowlines of gas wells occurs under conditions of high operating pressure and low temperatures. That is why we are interested in the soil freezing process and the analysis of the periods of the year with negative temperatures.

Soil temperatures at different depths and at different times of the year can be obtained by direct measurements in the wells. However, such a method is costly and not always economically feasible. In addition, data from several wells are approximated over large areas, which reduces the accuracy of the data obtained. In many cases, the calculated data are more reliable.

In accordance with the regulatory document (Svod pravyl, 2012), the following approach is recommended for calculating the soil freezing depth. The maximum soil freezing depth at the time of the forecast D_f, m is determined by the formula

$$D_f = d_{f,n}\sqrt{\frac{(\mathrm{T}_f - T_{bf})t_f}{(\mathrm{T}_{f,m} - T_{bf})t_{f,m}}}, \qquad (1)$$

where $d_{f,n}$ is the standard depth of seasonal freezing of soil, m; T_f - average air temperature from the onset of the negative temperature period to the moment of forecast, ^{0}C; t_f - duration of the negative temperature period up to the moment of forecast, sec; $T_{f,m}$ - mean air temperature of the negative temperature period according to long-term observations, ^{0}C; $t_{f,m}$ - average annual duration of the negative temperature period, sec; T_{bf} - temperature of the beginning of soil freezing (for loams it is assumed to be -0.2^{0}C (Svod pravyl, 2012)).

In the absence of field observations, the standard depth of seasonal freezing of soil $d_{f,n}$ can be determined with high accuracy based on the data of long-term observations of air temperature (Khrenkov, 2007):

$$d_{f,n} = \sqrt{\frac{2\lambda_f (T_{bf} - T_{f,m}) t_{f,m}}{q_2}}, \qquad (2)$$

where λ_f is the coefficient of thermal conductivity of frozen soil, W/(m·^{0}C); q_2 is the amount of energy required to freeze water in the soil:

$$q_2 = L_0 (w_{tot} - w_w)\rho - 0.5 C_f (T_{f,m} - T_{bf}), \qquad (3)$$

where L_0 is the heat of ice melting, J/kg; w_{tot} - total soil moisture; w_w - soil moisture due to unfrozen water; ρ - soil density, kg/m^3; C_f - volumetric heat capacity of frozen soil, J/(m^3·^{0}C).

On the basis of the data on climatic parameters (Table 1) and the characteristics of the soil cover (Table 2), according to the formula (2), the standard depth of soil freezing $d_{f,n}$ for a given territory has been determined:

$$d_{f,n} = \sqrt{\frac{2\lambda_f (T_{bf} - T_{f,m}) t_{f,m}}{L_0 (w_{tot} - w_w)\rho - 0.5 C_f (T_{f,m} - T_{bf})}}, \qquad (4)$$

It has been established that the standard depth of soil freezing in the territory of the Eastern Oil- and Gas-bearing province is 0.85 m. This value corresponds to the average depth of soil freezing in the territory of Ukraine.

Long-term observations of air temperature at the meteorological station were used to forecast the depth of soil freezing (Table 3). Only the periods of the year with negative temperatures, which for most of Ukraine last from early December to late February, have been taken into account. That is, the average annual period of negative temperatures is 90 days or 7776000 seconds.

Table 3 *Results of long-term observations of air temperature at the meteorological station in Izium*

Duration of the negative temperature period, $t_{f,m}$, [^{0}C]			The average temperature, [^{0}C]										
Month	Days from the beginning	Seconds from the beginning	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
December	31	2592000	-1	-1.9	-2.5	-2.6	-0.2	-1.7	-3.8	-1.3	-2.5	-0.6	-4.4
January	62	5184000	-10.4	-1.7	-6.2	-4.7	-8.3	-7.4	-4.4	-1.9	-6.1	-2.6	-6.4
February	90	7776000	-8.8	-3.4	-1.7	-0.7	-2.9	-9.2	-10.1	-0.1	-1.6	-1.8	-2.4
Mean air temperature of the negative temperature period, T_f, [^{0}C]			-6.7	-2.3	-3.5	-2.7	-3.8	-6.1	-6.1	-1.1	-3.4	-1.7	-4.4

The freezing depth of soil D_f was calculated by formula (1). The results are presented in Table 4. According to the table data, it is also easy to note the expansion of the soil freezing limit in accordance with the previous month's temperature behavior. The forecast freezing depth is reached within 30 days. Thus, the forecast advance period is 1 month.

Table 4 *Expansion of the soil freezing limit during the period of negative temperatures*

Month	Soil freezing depth, D_f, [м]										
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
December	0.24	0.34	0.40	0.41	0.02	0.32	0.50	0.28	0.40	0.17	0.54
January	0.87	0.47	0.76	0.69	0.75	0.78	0.73	0.44	0.75	0.44	0.85
February	1.16	0.67	0.82	0.72	0.86	1.11	1.11	0.43	0.81	0.55	0.93

Conclusions

Presented approach for calculating the depth of soil freezing, which is implemented through the calculations by formulas (1) - (4), has several advantages:

1. The algorithm considers the average values of temperature according to long-term observations, as well as the air temperature data before the forecast;
2. The estimated depth of soil freezing is based on the duration of the negative temperature period, the onset of which varies annually;
3. Formula (1) can be used to calculate the monthly expansion of the soil freezing limit according to the previous month's air temperature;
4. The depth of soil freezing can be forecasted with an advance of 1 month.

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