Numerical research of heat transfer processes at the drilling wells in permafrost rocks

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Abstract. Systematic numerical studies of processes that affect the rate of thawing during drilling of oil and gas wells in permafrost have been carried out. The influence of flow rate, temperature, drilling fluid rheology and drilling duration on the rate of permafrost thawing is studied. To reduce the rate of thawing, the use of polymer drilling fluids with additives of ethylene glycol is proposed.

1. Introduction

The main factor determining the conditions for drilling oil and gas wells in the Northern latitudes is the permafrost. Permafrost is rocks that are constantly in the conditions of negative temperatures. Construction and operation of oil and gas deposits in permafrost conditions are complicated by the problem of partial or complete soil thawing near the objects that are the source of heat. As a result, subsidence, landslide, voids are formed which may contribute to negative factors and accidents during the drilling and operation of wells. This leads to long-term repairs, well downtime and significant losses of drilling fluids.

A large number of works [1-2] are devoted to the computational study of the process of thawing of rocks around wells. Moreover, the majority of computational research in this area is devoted to the process of well thawing during their exploitation. Theoretical studies of heat transfer processes during drilling of wells, including in permafrost conditions, are much less known. First of all, it is worth noting the systematic studies of the Leningrad Mining Institute [3-4]. Various analytical and calculation models of thermal processes in wells during drilling have been developed. However, these models contained serious assumptions. Only the characteristics averaged over the well section were considered. The shape of the velocity and temperature profile in the drill pipe and an annular channel was neglected. Because of this, it was necessary to set the values of heat transfer coefficients on the well walls and drill pipes, which for drilling fluids with complex rheology are generally not known and vary significantly depending on the flow regimes and the properties of the drilling fluid. In addition, a change in the physical and thermophysical characteristics of the drilling fluid along the depth of the well was also neglected. While in reality, the viscous and rheological characteristics of the drilling fluid are highly dependent on temperature. The temperature dependence of the properties of the drilling fluid was ignored. It was assumed that the heat in the rock around the well extends only in the radial direction. The distribution of thermophysical properties of frozen rock over the depth was ignored and so on. In contrast to the studies previously conducted in this field, this work considered coupled heat transfer taking into account the process of thawing and circulation of drilling fluid in the well. This approach allows us to take into account the effect of real physical properties of drilling fluids (viscosity, rheology, thermal characteristics) and their flow regimes on the value of the heat transfer coefficient from the drilling fluid to the permafrost and propagation speed of the thawing zone around the well. Using this model, systematic numerical studies of processes affecting the rate of thawing during drilling of oil and gas wells in permafrost conditions were carried out. The influence of flow rate, temperature, drilling fluid rheology and drilling duration on the rate of permafrost thawing was studied. To reduce the rate of thawing, the use of ethylene glycol-based solutions for drilling was examined.

2. Numerical model of drilling fluid circulation in the well by the permafrost thawing and testing the numerical algorithm

A detailed description of the mathematical model used for thermohydraulic processes in a well during drilling under permafrost conditions is studied in [5-6]. The results of testing the numerical method described above are presented in [6,7]. Good agreement between the calculations and the experiment on the shape of the velocity profile of the drilling fluid and pressure drop in the well, as well as on the dynamics of the thawing process, was obtained. Here, the test results of the phase transition model are presented. The well-known problem of melting gallium was considered as a verification method for modeling problems with a phase transition [8]. A comparison of the numerical results of the melting process with the experimental data of Gau and Viskanta [8] is shown in figure 1. The agreement is quite good.

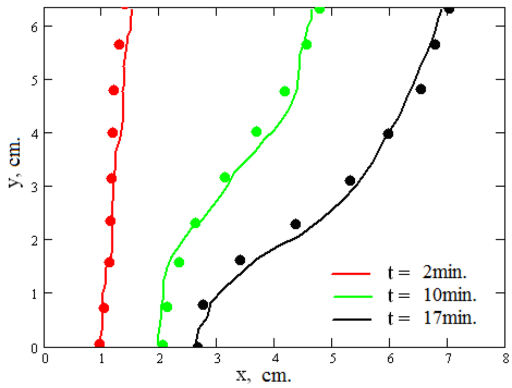


Figure 1. Melting front at different times. Solid lines – calculation, symbols – experimental data.

3. Results and discussion

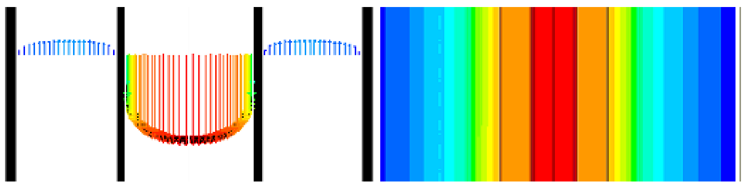
Based on the developed methodology, the rock thawing process in a well drilling was calculated using a drilling fluid based on a water-ethylene glycol mixture. The properties of drilling fluids with ethylene glycol are given in papers [5]. Thermal parameters of frozen rock (density ρ = 2110 kgm^{-3}, ice content i = 50%, thermal conductivity coefficient k = 1.67 Wm^{-1}K^{-1} and specific heat c_p = 2720 Jkg^{-1}K^{-1}) were used in calculations. The temperature of frozen rocks was set to -4 ºC.

In the simulation the geometrical parameters of the well corresponded to the typical structures used in drilling. The well diameter was 296 mm, the drill pipe diameter was d = 125 mm. The well depth was set to L = 400 m, which corresponds to the average depth of the permafrost.

The calculation was carried out in axisymmetric formulation. The radius of the calculated area was 100 m, the depth was 600 m. A grid consisted of 600,000 cells. The grid was thickened to the walls of the drill pipe and the well. Such dimensions of the calculated area and grid detailing do not affect the simulation results. The mud flow rate ranged from 10 to 60 ls^{-1}. The temperature of drilling fluid was ranged from +5°C to +30°C. After passing through the drill pipe to the end of the well, the drilling fluid turns around and rises to the surface through the annular gap. Neumann conditions were specified at the exit from the well.

The maximum of the drilling duration in the calculation was 10 days. An assumption was used that the drilling fluid was fed into the well with fixed flow rate and the drilling was continuous. The heating of drilling fluid due to friction on the well wall and bit was not consideration.

Figure 2 shows typical axial velocity profiles in the drill pipe and borehole and the temperature of the drilling fluid and the rocks adjacent to the well. First, the drilling fluid moves down the drill pipe. Then it returns to the surface along the annular channel. This one is shown in figure 2(a). During the movement, the drilling fluid exchanges heat through the walls of the drill pipe and the borehole. The temperature distribution over the radius at a depth of 200 m at a flow rate of 40 ls^{-1} of drilling fluid for different drilling durations is shown in figure 3(a). As you can see, in one day of drilling, the radius of the permafrost thaw was approximately $r = 0.23$ m. With an increase in the duration of drilling to 10 days, the thawing radius increases to 0.4 m. Thus, as the main measure to reduce the rate of thawing when drilling wells, it is necessary to consider a decrease in the duration of heat exposure as a result of an increase in the penetration rate.



a) b)

Figure 2. Velocity profile (a) and temperature distribution (b) in the well and near-well area for the base drilling fluids at a depth of 300 m in 2 days from the start of drilling.

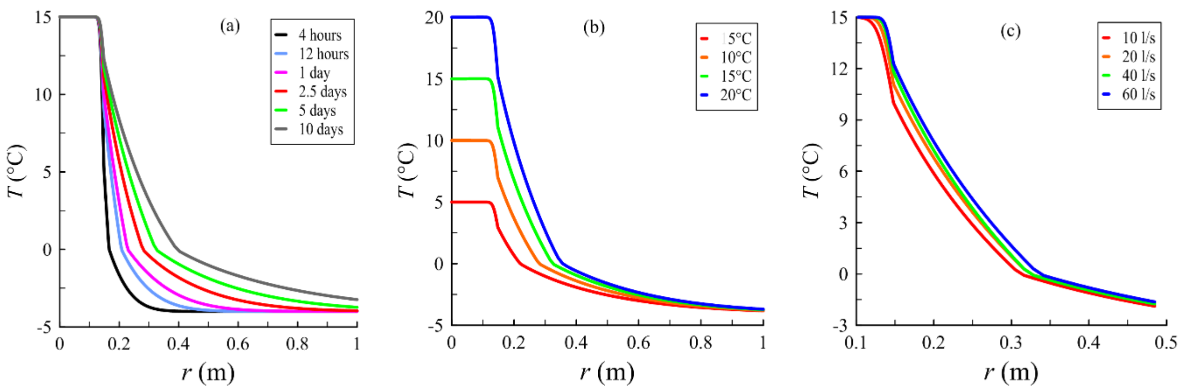


Figure 3. Temperature distribution over the radius at a depth of 200 m from the start time of drilling using by base drilling fluids at different drilling duration (a), after 5 days at different temperature of drilling fluid (b) and at different drilling mud flow rates (c).

The next factor affecting the rate of thawing during drilling was considered the temperature of the drilling fluid at the entrance to the well. The results of this study are shown in figure 3 (b). As expected, the temperature of the drilling fluid significantly affects the rate of thawing. A decrease in the temperature of the drilling fluid from 20°C to 5°C leads to a decrease in the radius of thawing from 0.35 m to 0.2 m with a drilling time of 5 days. Thus, to reduce the negative thermal effects, it is recommended to use drilling fluid with a minimum temperature for drilling frozen rocks. However, this is not always possible in practice.

The following factor influencing the rate of thawing during permafrost drilling was studied the effect of drilling fluid flow. The results of this study are shown in figure 3 (c). With an increase in the flow rate of the drilling fluid, on the one hand, the amount of heat entering the well increases, and on the other hand, the value of the heat transfer coefficient on the well walls increases. Due to this fact, the temperature on the well wall rises. This fact is well illustrated in figure 3 (c). This leads to an increase in the rate of the process of permafrost thawing around the well. However, this factor is less significant compared with the duration of drilling and the temperature of the drilling fluid. So, with an increase in the flow rate of the drilling fluid from 10 to 60 ls^{-1}, the thawing radius changed slightly from 0.30 to 0.35 m on the 5th days.

It is shown that a decrease in drilling time or an increase in penetration rate significantly reduces the rate of permafrost thawing. A rise in penetration rate in this case requires an increase in the flow rate of the drilling fluid for the removal of slime. Increasing the flow rate of the drilling fluid rises the rate of thawing. Thus, it is necessary to search for the optimal value of drilling fluid flow rate at which the thawing rate will be minimal.

Further, the effect of ethylene glycol additives on the thawing rate was analyzed. The thermal conductivity and heat capacity of the drilling fluid are very important for reducing thawing rate in the drilling. With an increase in the mass content of ethylene glycol the thermal conductivity coefficient and the heat capacity of the solution decrease significantly. Reducing the thermal conductivity coefficient of the drilling fluid during permafrost drilling is a favorable condition for reducing the thawing rate, since the heat transfer coefficient from the solution to the well walls decreases. The dependence of the area average heat transfer coefficient $\bar{\alpha}$ from the drilling fluid to the well wall on the ethylene glycol content is shown in figure 4(a). With an increase in the ethylene glycol content in the drilling fluid the heat transfer coefficient decreases monotonously. So the heat transfer coefficient is almost two times less as compared to the base solution at the concentration of ethylene glycol of 80wt.%. The heat transfer coefficient practically does not change with time, with the exception of the first half hour. The dependence of the heat transfer coefficient established over time on the content of ethylene glycol in the drilling fluid for different values of the flow rate of the drilling fluid is shown in figure 4(b). With increasing ethylene glycol content, the average value of the heat transfer coefficient decreases almost linearly for all values of the flow rate of the drilling fluid.

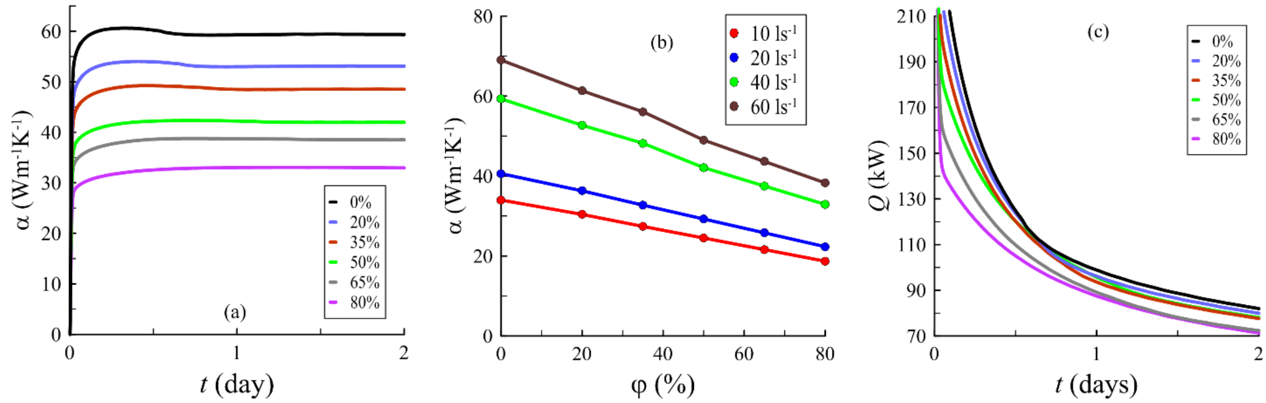


Figure 4. The time dependent (a) and averaging (b) of heat transfer coefficient of the well walls and the heat flow entering the well with drilling fluid (c).

The decrease in heat transfer coefficient leads to the decrease the temperature on the well walls, which leads to a decrease in the thawing rate. The temperature distribution over the radius at a depth of 200 m with different ethylene glycol content in the drilling fluid is shown in figure 5. The temperature decrease on the well walls by reducing the heat transfer coefficient is about 3°C in relation to the base drilling fluid. Reducing the heat capacity of the drilling fluid with the ethylene glycol addition is also a favorable condition, in this case the heat entering the well with the drilling fluid decreases. Figure 4(c) illustrates the time dependence of the heat flow at different contents of ethylene glycol in the drilling fluid. With increasing ethylene glycol content the heat entering the well decreases. This effect on the first day after the start of circulation. As it warms up near the well area the heat flow decreases monotonously. The effect of the addition of ethylene glycol in the drilling fluid reduces also. A decrease in the heat transfer coefficient and heat entering the well with the ethylene glycol addition to the drilling fluid leads to a significant slowdown in the process rate of permafrost thawing.

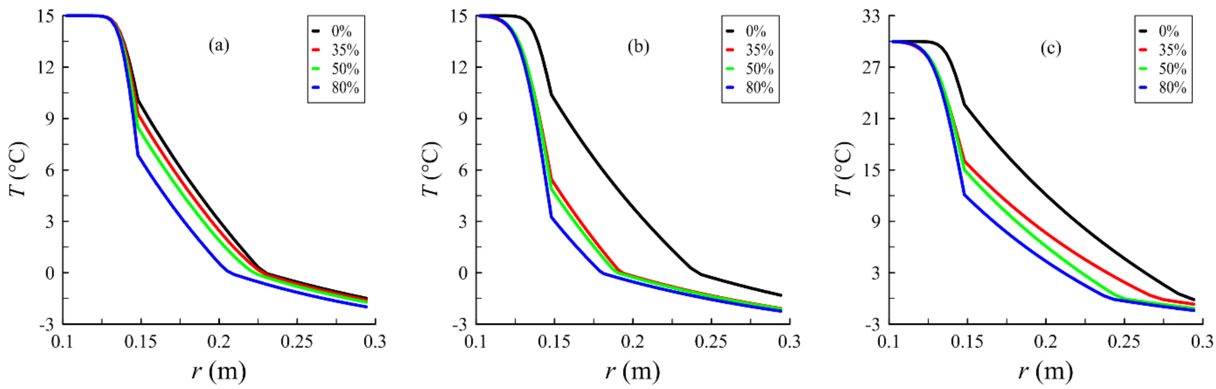


Figure 5. The temperature profiles: a) the mud flow rate 40 ls^{-1} and the temperature +15°C; b) the mud flow rate 10 ls^{-1} and the temperature +15°C; c) the mud flow rate 10 ls^{-1} and the temperature +30°C.

Next, the influence of drilling fluid flow rate on the rate of the thawing process during drilling with ethylene glycol-added fluids was investigated. These results are shown in Figure 5 (b). With a decrease in the flow rate of the drilling fluid, the positive effect of the addition of ethylene glycol on the rate of the thawing process slightly increases. Moreover, as shown above, the flow rate has a weak effect on the rate of thawing. A more significant effect is the temperature of the drilling fluid. The effect of ethylene glycol additives on the rate of permafrost thawing for the inlet temperature of the drilling fluid 30C is shown in Figure 5 (c). With increasing inlet temperature of the drilling fluid, the positive effect of the additive increases. So, at a drilling fluid temperature of 15°C, the addition of 80% by weight of ethylene glycol reduces the thawing radius by 1.1 times, and at a temperature of 30°C by 1.3 times.

4. Conclusion

It is shown that the most significant factors are the temperature of the drilling fluid and the duration of the drilling process. To reduce the rate of thawing, the use of polymer drilling fluids with additives of ethylene glycol is considered. It was found that with an increase in the ethylene glycol content in the drilling fluid the heat transfer coefficient from the drilling fluid to the well wall decreases significantly. With the concentration of ethylene glycol of 80 wt.%, the heat transfer coefficient reduced almost twice as compared with the base drilling fluid. At the same time with an increase in ethylene glycol content there is a significant decrease in the heat entering the well. A decrease in the heat transfer coefficient and heat entering the well with the ethylene glycol addition to the drilling fluid leads to a significant slowdown in the process rate of permafrost thawing. Analysis of the numerical simulation showed that with an increase in the ethylene glycol content, a monotonous decrease in the average thawing radius of the rock in region around the well is observed. It was found that the use of ethylene glycol additive is most effective at high drilling fluid temperatures.

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