NUMERICAL SIMULATION STUDY ON THE ACTION LAW OF LOW TEMPERATURE DRILLING FLUID INTRUSION INTO ROCK FORMATION IN POLAR DRILLING

by

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Original scientific paper
https://doi.org/10.2298/TSCI230718018W

In this paper, based on the experimental parameters of polar permafrost formation, the mathematical module, solid mechanics module, and Darcy's law module of COMSOL Multiphysics software are used to realize the coupled solution of PDE of temperature field, moisture field, and stress field considering the ice-water phase transition and moisture convection, and the relationship between the permafrost moisture convection and temperature change is analyzed by using the heat-flow-solid-moisture mutual coupling, which reveals that the law of action of low temperature intrusion into rock formation by polar drilling.

Key words: *polar permafrost, cryogenic drilling mud invasion, open problems, wellbore-reservoir coupling, numerical simulation*

Introduction

At this stage, with the continuous improvement of drilling technology, researchers are gradually focusing on unconventional reservoir oil and gas exploration. Since the USA explored rich oil and gas resources in the Arctic region in 2008, various countries have also carried out oil and gas exploration and development of the Arctic Antarctic and other polar tundra [1, 2]. However, there are few reports of successful drilling cases in the polar regions, as the drilling problems related to the polar tundra are still being explored [3].

Most of the polar drilling is permafrost rock samples [4]. Permafrost is a temperature-sensitive porous elastic-plastic material and when the low temperature drilling fluid invades the contrasting permafrost layer due to the pressure and temperature changes, it will make the formation of internal phase changes. Since permafrost has the property of freezing, swelling, thawing, and sinking, the phase change of water will lead to the redistribution of stress and strain in the formation, thus affecting the stability performance of the well wall [5, 6].

Aiming at the aforementioned problems, this paper carries out the secondary development by mathematically analyzing the temperature field, pressure field, moisture field, and strain field of the polar permafrost formation in the process of drilling fluid intrusion, using the coefficient-type PDE in COMSOL Multiphysics finite element software [7, 8]. According to the thermodynamic properties of permafrost, the changes in the temperature field, pressure field,

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and stress field of the reservoir by the temperature intrusion of low temperature drilling fluid into the polar formation are analyzed, and a coupled model of heat-fluid-solid multiphysics field is established [9, 10]. The interaction law between the low temperature drilling fluid and the contrasting permafrost rock layer is revealed using simulation numerical modelling, which provides a relevant theoretical basis for the subsequent drilling exploration and exploitation of the polar permafrost layer [11].

Multi-physics field modelling

Using a set of multi-physics control equations for temperature, moisture, pressure, and stress fields, a model was built using COMSOL Multiphysics, and the results of numerical simulation calculations were used to reveal the pattern of the drilling fluid when it intruded into the polar rock formation.

Geometric model

The polar permafrost was constructed as a 2-D model with a length of 0.2 m and a height of 0.1 m. A user-defined rectangular grid is created using COMSOL. The finite element model is divided into 5000 domain cells and 300 boundary cells, and the computation period is three days with a step size of 1 hour.

Parameter selection and determination of boundary conditions

The values of thermodynamic parameters of each material of this calculation refer to the contents of references such as *Physics of Permafrost*, and the hydraulics parameters are quoted from *Unsaturated Soil Mechanics*, *etc.*

In the model boundary definition, since this model is the drilling fluid intruding into the formation from the left side to interact with the rock, the upper and lower boundaries of the model are regarded as adiabatic and no flux boundaries. There is no heat and mass exchange between the upper and lower sides and the outside world, and the left boundary is the intrusion temperature of the drilling fluid and the boundary load pressure. The material parameters and boundary constraints are added, the right boundary is set as a fixed constraint, and the upper and lower boundaries are set as roll supports. The grid is divided for transient calculations.

Analysis of results

Based on the pre-assumed conditions, this problem can be viewed as a radial displacement problem of drilling fluid in two dimensions, and the results mainly contain temperature field analysis, pressure field analysis, and permafrost strain analysis.

Temperature field analysis

When 0° drilling fluid intrudes into the 5° formation, the convection and diffusion of heat will cause the temperature within the formation increase, and the specific changes are shown in figs. 1 and 2.

As shown in fig. 1, the temperature of the drilling fluid is higher than that of the permafrost, so the formation temperature gradually increases with time, but the overall temperature change is not drastic because the melting of the permafrost ice layer will absorb the corresponding heat and lead to a further reduction of the formation temperature, and the formation temperature change is minimal after 30 hours. The temperature change within 0.2 m near the wellbore is minimal, indicating that under the initial pump-in pressure of 11 MPa, the formation temperature is 9 MPa. The temperature change within 0.2 m near the wellbore is minimal. The change is mainly concentrated in 0.1 m outside the wellbore, which indicates that under the initial pumping pressure of 11 MPa, the drilling fluid intrusion into the 9 MPa formation is not very deep. It can be seen in fig. 2 that the rate of change of the formation temperature and the final value will be reduced with the increase of the depth of the intrusion of drilling fluid. The temperature at 0.03 m increased by 3.48 within 72 hours, the temperature at 0.03 m increased by 3.48 °C. In comparison, the formation temperatures at 0.12m and 0.18m only increased by 1.65 °C and 0.41 °C, with an average temperature change gradient of 10.8 °C/m.

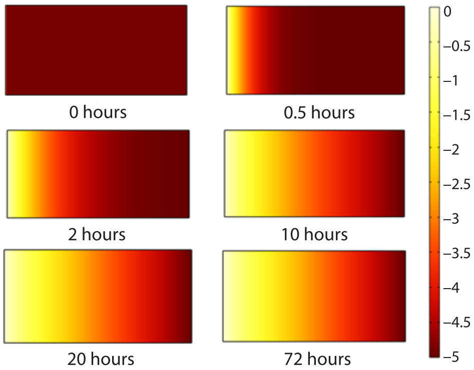

Figure 1. Temperature cloud of 0 °C drilling fluid intrusion into the formation

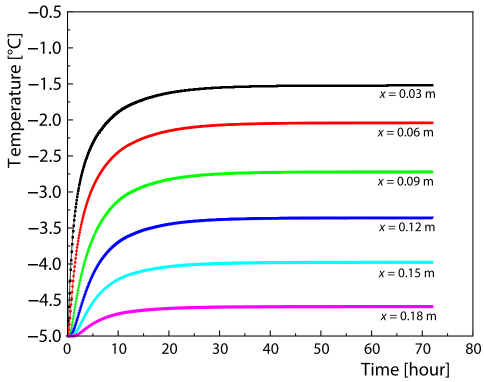

Figure 2. Stratigraphic temperature variations at different locations of 0 °C drilling fluid intrusion into the formation

Pressure field analysis

When the drilling fluid intrudes into the polar permafrost at 11 MPa, the pressure-driven motion of the drilling fluid approximately follows Darcy's law, which in turn causes the formation pressure to redistribute as well.

As can be seen from the pressure change cloud diagram in fig. 3 and the pressure change diagram in fig. 4 of the formation at different locations, the pressure at each formation area gradually increases with time due to the intrusion of drilling fluid from high pressure to low pressure. In the early stage of the change, due to the movement of the water field within the formation from static, the pressure at each location initially fluctuates slightly.

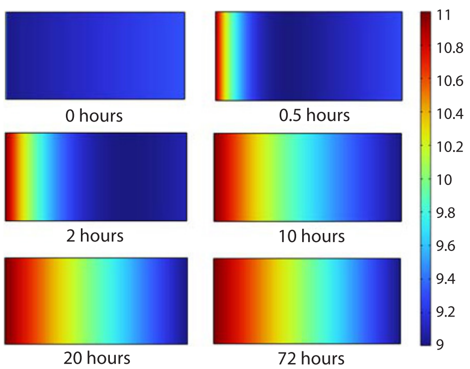

Figure 3. Pressure cloud of 0 °C drilling fluid intrusion into the formation

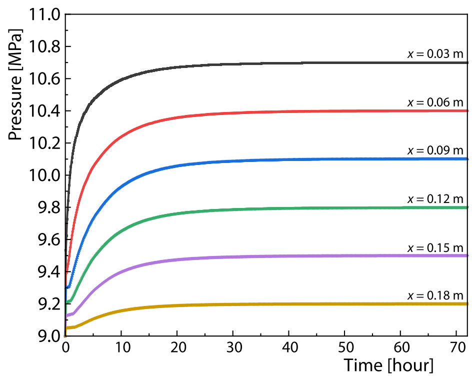

Figure 4. The pressure variations at different locations of 0 °C drilling fluid intrusion into the formation

Still, in general, it shows an upward trend. As the distance from the wellbore increases, the pressure value and the range of pressure change gradually decrease, and the pressure change within 0.2 m near the wellbore is small. The change is mainly concentrated in 0.1 m outside the wellbore, which is also coupled with the temperature change. Within 72 hours, the pressure at 0.03 m increased by 1.70 MPa, while the formation temperatures at 0.12 m and 0.18 m only increased by 0.80 MPa and 0.20 MPa, and the average pressure drop gradient was 4.75 MPa/m. The pressure drop gradient at 0.12 m and 0.18 m was 0.80 MPa and 0.20 MPa, respectively.

Strain field analysis

When the drilling fluid intrudes into the polar permafrost, it causes a relative increase in the absolute value of the volumetric strain inside the formation due to the permafrost ice-water phase change, as shown in figs. 5 and 6.

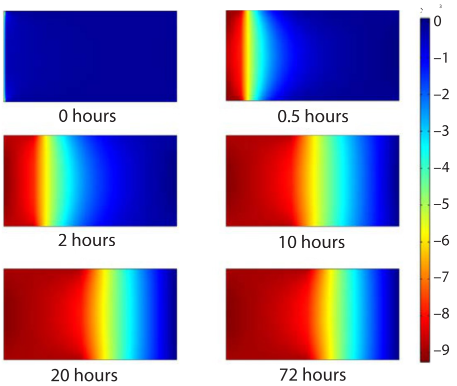

Figure 5. Volumetric strain cloud of 0 °C drilling fluid intrusion into the formation

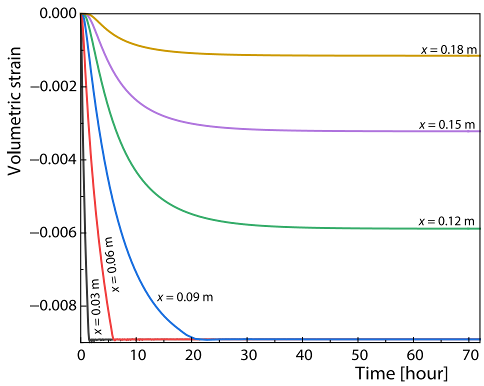

Figure 6. Variation of formation volumetric strain at different locations of 0 °C drilling fluid intrusion into the formation

From the variation of volumetric strain in fig. 5 and the variation of volumetric strain in the formation at different locations in fig. 6, it can be seen that, due to the principle of frost heave and thaw settlement inside permafrost, in permafrost drilling operation, the temperature difference between the drilling fluid and the formation generates thermal stresses. The heat transfer between the two will change the mechanical parameters of the formation, which in turn affects the stability of the formation. When 0 °C drilling fluid intrudes into the formation, the ice layer's melting causes the formation volume to decrease, and the volumetric strain is negative. With the influence of phase change and water displacement, the rate of change of the volumetric strain and the final value gradually decreases with the increase of the distance from the wellbore, which indicates that the intrusion range of drilling fluid is still the most drastic in the range of less than 0.1 m. It corresponds to the temperature and pressure field mentioned previously. Within 72 hours, the volumetric strain value at 0.03 m changed by 8.91×10^{-3}, while the formation temperatures at 0.12 m and 0.18 m only increased by 5.88×10^{-3} and 1.15×10^{-3}, and the average volumetric strain gradient was 3.08×10^{-2} per m, which was a slight change.

Conclusion

Through COMSOL Multiphysics numerical simulation of low temperature drilling fluid intrusion into the polar permafrost, it is concluded that the temperature and pressure of drilling fluid will affect the original state of the formation when the drilling fluid at 0 °C with 11 MPa intrudes into the polar formation with the actual temperature and pressure of –5 °C and 9 MPa, the temperature and pressure of the formation will increase to different degrees. With the increased distance from the borehole, the final value and the rate of change will be relatively weakened.

Acknowledgment

This work was supported by the China University of Petroleum (East China) Independent Innovation Research Program Project (27RA2302016), the National Natural Science Foundation of China (No. 52274025 and 51991361), the National Key Research and Development Program of China (2021YFC2800803), the CNPC's Major Science and Technology Projects (No. ZD2019-184-003), and the Key R & D Program of Shandong Province (No. 2020ZLYS07).

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Paper submitted: July 18, 2023
Paper revised: August 21, 2023
Paper accepted: November 18, 2023