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A borehole temperature during drilling in a fractured rock formation

S. Fomin [a,*], T. Hashida [b], V. Chugunov [c], A.V. Kuznetsov [d]

[a] *Department of Mathematics and Statistics, California State University, Chico, CA 95929-0525, USA*
[b] *Fracture Research and Reliability Institute, School of Engineering, Tohoku University, Sendai 980 8579, Japan*
[c] *Department of Applied Mathematics, Kazan State University, Kazan 420008, Russia*
[d] *Department of Mechanical & Aerospace Engineering, North Carolina State University, Raleigh, NC 27965-7910, USA*

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Abstract

Drilling in brittle crystalline rocks is often accompanied by a fluid loss through the finite number of the major fractures intercepting the borehole. These fractures affect the flow regime and temperature distributions in the borehole and rock formation. In this study, the problem of borehole temperature variation during drilling of the fractured rock is analyzed analytically by applying the approximate generalized integral-balance method. The model accounts for different flow regimes in the borehole, for different drilling velocities, for different locations of the major fractures intersecting the borehole, and for the thermal history of the borehole exploitation, which may include a finite number of circulation and shut-in periods. Normally the temperature fields in the well and surrounding rocks are calculated numerically by the finite difference and finite element methods or analytically, utilizing the Laplace-transform method. The formulae obtained by the Laplace-transform method are usually complex and require tedious numerical evaluations. Moreover, in the previous research the heat interactions of circulating fluid with the rock formation were treated assuming constant bore-face temperatures. In the present study the temperature field in the formation disturbed by the heat flow from the borehole is modeled by the heat conduction equation. The thermal interaction of the circulating fluid with the formation is approximated by utilizing the Newton law of cooling at the bore-face. The discrete sinks of fluid on the bore-face model the fluid loss in the borehole through the fractures. The heat conduction problem in the rock is solved analytically by the heat balance integral method. It can be proved theoretically that the approximate solution found by this method is accurate enough to model thermal interactions between the borehole fluid and the surrounding rocks. Due to its simplicity and accuracy, the derived solution is convenient for the geophysical practitioners and can be readily used, for instance, for predicting the equilibrium formation temperatures.

Keywords: Fluid loss; Borehole; Temperature; Heat flux; Bore-face; Fluid circulation; Integral-balance method

1. Introduction

A reliable assessment of thermal interaction between the borehole and the surrounding rock formation is of considerable interest in a number of geophysical

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[*] Corresponding author. Tel.: +1 530 898 5274.
E-mail address: sfomin@csuchico.edu (S. Fomin).

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Nomenclature

A, B	constants which define the equilibrium temperature of the rock formation, $t_f(z^*) = Az^* + B$
a_i^d, a_i^a, b_i, a_i^d, c_i^a, c^d	coefficients in Eqs. (9) and (10), which are defined by Eqs. (15)
Bi, Bi_i	Biot numbers defined by Eqs. (7) and (17), respectively
c_r, c_L	specific heat of the rock and fluid, respectively
$c_i^{(1)}$, $c_i^{(2)}$	constants of integration in Eqs. (32) and (33)
d_r, d_L, d_p	thermal diffusivities of the formation, liquid and drilling pipe, respectively
d_i	parameters defined by Eq. (34)
f	non-dimensional geothermal gradient defined by Eqs. (16)
G	flow rate in the drilling pipe
G_i	the flow rate in the annulus between the fractures $(i - 1)$ and i
H	depth of the borehole during drilling (a function of time)
H_0	initial depth of the borehole at the onset of the next drilling cycle
h^w	heat transfer coefficient on the bore-face
h^d, h_i^d	heat transfer coefficients on the inner and outer walls of the drilling pipe
h_i	coefficient defined by Eqs. (17)
J_0, J_1	Bessel functions of the first kind of the order 0 and 1, respectively
q_i	heat fluxes on the bore-face defined by Eqs. (22) and (25)
$\bar{q}_i$	function defined by Eq. (36)
k_r, k_L, k_p	thermal conductivities of the formation and fluid and drilling pipe, respectively
l	radius of thermal influence
N	number of fractures intercepting the well
r_0	external radius of the drilling pipe
r_w	radius of the borehole
r, z	non-dimensional cylindrical coordinates
T_r	non-dimensional temperature of the formation during drilling defined by Eqs. (7)
T_i^a, T_i^d	non-dimensional temperature of fluid in the annulus and drilling pipe defined by Eqs. (16)
T_{in}	non-dimensional temperature injected fluid defined by Eqs. (16)
t^a, t^d	temperatures in the annulus and drilling pipe, respectively
t_r	temperature of formation during fluid circulation
t_{in}	temperature of injected fluid
t_f	equilibrium temperature of formation
t_0	temperature in formation defined by Eq. (8)
U_0, U^a, U^d	non-dimensional temperatures defined by Eqs. (42)
V	drilling velocity
v^d, v_i^a	mean fluid velocities in the drilling pipe and in the annulus, respectively
z_i	location of the ith fracture intercepting the well
Y_0, Y_1	Bessel functions of the second kind of the order 0 and 1, respectively
δ	thickness of the drilling pipe wall
η	function defined by Eqs. (31)
$\lambda_i^{(1)}$, $\lambda_i^{(2)}$	parameters defined by Eq. (35)
$\bar{\lambda}_i^{(1)}$, $\bar{\lambda}_i^{(2)}$	parameters defined by Eq. (41)
μ	fluid viscosity
ρ_r, ρ_L	densities of rock and liquid, respectively
τ	time
τ_H^*	time, required to drill a well to the depth H

Superscripts

a	annulus
d	drilling pipe
w	wall of the borehole
*	dimensional quantities

Subscripts

d	drilling pipe
i	ith section in the borehole between fracture $(i - 1)$ and i
L	liquid
m	mean value
r	rock
w	wall of the borehole

applications. The following applications are worth mentioning: (i) interpretation of electric logs and estimation of the formation temperatures from well logs, which requires knowledge of temperature disturbances in the formation produced by circulating fluid during drilling [1–4]; (ii) optimal design of the drilling bit cooling system within the high-temperature formation [5] requires assessment of the heat either delivered from the high temperature rocks to the drilling bit or transmitted to the formation from the circulating fluid; (iii) developing the new technologies and methods in the area of geothermal energy production [6–8]. Normally, temperature fields in the well and surrounding rocks are calculated numerically [1,2,9–12] by using a finite difference method.