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A generalized mathematical model to predict transient bottomhole temperature during drilling operation

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ABSTRACT

This paper discusses a generalized mathematical model to calculate the transient and steady state temperatures for drilling mud, applicable for both offshore and onshore wells. Finite difference method is used to develop the numerical model, every effort was made to incorporate all possible components involved during onshore and offshore drilling operation. The model applicability extends from a very simple vertical mono-bore to complex horizontal wellbore geometry to enable to estimate drilling mud, casing, tubing and near formation temperature in conventional as well as HPHT well. To represent the dynamic nature of heat transfer more closely, pressure and temperature dependent mud properties and flow-based heat transfer coefficients are utilized into the model.

The model's transient bottomhole circulating temperature for simple cases is compared with published models and results are found in agreement Edwardson et al. (1962) regarding the disturbance due to mud circulating beyond 10 ft. from the wellbore is insignificant, is also verified. Besides, the behavior of downhole temperature during make-up and the riser's effect on temperature profile are evaluated. This report also discusses the influence of job controlling parameters such as flow rates, inlet temperature, fluid density and fluid rheology.

1. Introduction

The demand for oil and gas is pushing the petroleum industry into more challenging, hotter environments to extract oil & gas. The presence of harsh conditions requires even more challenging needs to determine what temperatures to expect while drilling petroleum well. The existence of abnormal temperature gradients may lead to a number of problems e.g., malfunctioning of downhole electronics, downhole equipment failure, casing and liner integrity, loss of drilling mud properties, formation integrity or even loss of a well. These challenges can only be partly met by having more resilient materials to sustain such conditions. Therefore, part of the solutions must be improved procedures, which require a better understanding of downhole temperature regimes.

One important challenge is to protect downhole electronics from heat-induced failure. Engineers and researchers have been working since 1980s to develop new materials for electronics to be used at extreme temperatures. For example, Prime Directional Systems along with other researchers are putting great effort to develop Measurement While Drilling (MWD) or Logging While Drilling (LWD) tools specified to survive temperatures up to 225 °C. However, the development of thermal resistant materials needs more research and time to reach this goal. At the same time, there have been continuous efforts to develop mathematical models to simulate downhole temperature accurately. These models have been successfully applied in drilling, cementing and production applications. During drilling a well, it is essential to ensure that the downhole temperature does not exceed the rating of electronics. The life of electronics installed in MWD tool is vulnerable to exposed temperature while drilling, because each 10 °C change in operating temperature doubles or cuts in half the electronics' lifetime.[1] The reliability of electronics can be improved by either improving the thermal rating of the electronics or controlling the downhole temperature.

Besides influencing the drilling tools, the temperature is also affecting on the rheology of the drilling mud. Theoretically, increase in intermolecular distances due to high temperature will lower the resistance of the fluid to flow and, hence, its viscosity, yield point, and gel strength will decrease. The rheological

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[1] Based on the Arrhenius equation, which says that time to failure is a function of $e^{-Ea/kT}$, where Ea is the activation energy of the failure mechanism being accelerated, k is the Boltzmann's constant, and T is the absolute temperature.

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Nomenclature

T	temperature, °C
P	pressure, Pa
ρ	drilling mud density, kg/m^3
f	fraction
τ	shear stress, Pa
μ	viscosity, Pa s
γ	shear strain, m/m
d	inside pipe diameter, m
D	outside pipe diameter, m
d_e	equivalent diameter, m
ν	velocity, m/s
Re	Reynolds number
L	conduit length, m
Pr	Prandtl number
h	heat transfer coefficient, W/m^2 °C
k	thermal conductivity, W/m °C
C	specific heat capacity, J/kg °C
W	wetted perimeter, m
A	area, m^2
z	arbitrary depth, m
O	order of
α	thermal diffusivity
t	time, s
r	radius, m
U	overall heat transfer coefficient, W/m^2 °C
R	thermal resistance, mk/W
$\dot{m}$	mass flow rate, kg/s
Q	heat transfer, J/s
g	acceleration due to gravity, m/s^2
psi	pound per squared inch
ppg	pound per gallon
gG	geothermal gradient, °C/m

Subscripts

f	drilling fluid
D	dimensionless
h	hydraulic diameter
a	annulus
o	oil
w	water
s	solid
y	yield point
yo	reference yield point
P	plastic
p	drill pipe
c	casing

properties of drilling fluids are usually approximated to be independent of pressure and temperature. In many cases this is a good approximation. For shallow wells the temperature changes are not so large, and hence the rheological variations with temperature are small. Also, many wells have a large gap between pore pressure and fracture pressure, so errors in the estimation of the dynamic circulation pressure have no consequences for well integrity or kick probability.

However, for wells with small margins between pore and fracture pressure, careful evaluations and analysis of the effects of temperature and pressure on wellbore hydraulics and kick probability is needed. In such cases, failure to predict the mud properties may cause serious well-control problems. It could lead to wrong predictions of pressure drop and ECD. Eventually, resulting in wellbore collapse, immature failure of drill strings or casings, influx (kick) or even loss of a well. Being able to predict the temperature within the wellbore, the behavior of the drilling mud can be tested in the laboratory prior to its application and hence these risks can be reduced.

The estimation of downhole temperature and pressure enables us to improve well design and well operations. There are other areas which require the estimation of the wellbore temperature. For example, the design of equipment for drilling, stimulation and production requires downhole temperature estimation to account for the induced thermal stress due to temperature changes.

The need to have wellbore temperature profile is quite imperative, and it is required in different phase in petroleum industry, e.g.

- Drilling mud rheology and design.
- Cementing program design.
- Thermal integrity of wellbore.
- Determination of casing and tubing thermal stresses.
- Selection of blowout preventer (BOP) elastomers and qualification of downhole drilling and testing tools.
- Completion fluid selection to optimize hydrate prevention.
- Packer design and selection.
- Drill bit design.

2. Literature review

Over the years two approaches have been applied to estimate the circulating drilling fluid temperature:

- Analytical method
- Numerical method

3. Analytical method

Analytical method solves the governing heat transfer equations in the wellbore analytically. i.e., assuming constant fluid and formation properties. The mathematical equations are often further simplified by eliminating time dependency, i.e., no change in temperature with respect to time, to get steady state solution. Owing to these simplifications, analytical approach is applied to system geometries of lesser complexity such as mono-bore well and single temperature gradient. Therefore, most engineering problems are first solved analytically to get simple and quick solution before divulging into a more complicate system. A brief overview of work done by various researchers to predict wellbore temperature using analytical method is presented below.

Crawford et al. (1967) developed a method to calculate transient temperature during a cementation operation. They investigated the importance of downhole temperature to cement slurries design and developed the techniques to calculate the temperature in annulus for cementing operation. Crawford concluded the maximum temperature of circulating mud does not occur at the bottom of drilling well. However, their work was specific to transient cementing temperature and cannot be considered as a generalized computation tool.

The first analytical model for wellbore temperature was presented by Holmes and Swift (1970). They solved the heat transfer

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