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Research Paper

Determination of transient temperature distribution inside a wellbore considering drill string assembly and casing program

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HIGHLIGHTS

- The different wellbore conditions of heat transfer models were developed.
- Drill string assembly and casing programs impact on down-hole temperatures.
- The thermal performance in circulation and shut-in stages were deeply investigated.
- Full-scale model coincided with the measured field data preferably.

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ABSTRACT

Heat exchange efficiency between each region of the wellbore and formation systems is influenced by the high thermal conductivity of the drill string and casing, which further affects temperature distribution of the wellbore. Based on the energy conservation principle, the Modified Raymond, Simplified and Full-scale models were developed, which were solved by the fully implicit finite difference method. The results indicated that wellbore and formation temperatures were significantly influenced at the connection points between the drill collar and drill pipe, as well as the casing shoe. Apart from the near surface, little change was observed in temperature distribution in the cement section. In the open-hole section, the temperature rapidly decreased in the circulation stage and gradually increased in the shut-in stage. Most important, the simulated result from the full-scale model coincided with the measured field data better than the other numerical models. These findings not only confirm the effect of the drill string assembly and casing programs on the wellbore and formation temperature distribution, but also contribute to resource exploration, drilling safety and reduced drilling costs.

1. Introduction

With the development of human society, world energy consumption will continue to increase in the coming decades. Consumption is expected to reach 20,679 million tons of oil equivalent (Mtoe) in 2040, including 28% from oil, 27% from coal, 23% from natural gas, 15% from renewables, and 8% from nuclear energy sources [1–5]. As a result, hydrocarbon resources play a significant role in supplying the global energy market through 2040. Geothermal energy, a renewable and sustainable energy, is transferred from the interior to the surface of the Earth with approximately 592,638 TJ/year harnessed in 82 countries [6,7]. It is well known that in order to obtain this resource, geothermal wells are drilled at selected locations to establish a channel from the bottom-hole to the surface. Globally, increasing amounts of hydrocarbon and geothermal resources are being found in fields that have very high thermal gradients, resulting in a series of technical challenges in the high temperature environments of drilling and production processes [8].

As the total vertical depth increases, there is an increase in the bottom-hole temperature, as well as the hydrostatic fluid column pressure. These two factors have opposing effects on fluid density. The increased hydrostatic fluid column pressure causes an increase in the fluid density due to compression. Conversely, the increase in temperature causes a decrease in the fluid density due to thermal expansion [9]. It is inferred that the two effects cancel each other out in shallow well drilling, which could ensure drilling safety using the formation temperature instead of the wellbore temperature. In

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Nomenclature

C_p	specific heat at constant pressure [J/kg °C]
c_f	specific heat capacity of the formation [J/kg °C]
c_m	specific heat capacity of the drilling fluid [J/kg °C]
c_w	specific heat capacity of the drill string [J/kg °C]
c_4	specific heat capacity of the borehole wall medium [J/kg °C]
$\tilde{F}$	deviatoric stress tensor of the fluid flow in the wellbore
G_f	geothermal gradient [°C/100 m]
h_1	convection coefficient of the inner wall of the drill string [W/(m^2 °C]
h_2	convection coefficient of the outer wall for the drill string [W/(m^2 °C]
h_3	convection coefficient of the borehole wall [W/(m^2 °C]
i	node number in the r direction
j	node number in the z direction
n	time node
Q_a	energy source of unit length inside the annular [W m^{-1}]
Q_m	energy source of unit length inside the drill string [W m^{-1}]
q_s	heat source term [W m^{-1}]
q_f	heat resulting from fluid friction losses [W m^{-1}]
q_{in}	heat resulting from heat exchange among regions [W m^{-1}]
q	flow rate of the drilling fluid [m^3/s]
r_f	formation radius [m]
r_1	inside radius of the drill string [m]
r_2	outer radius of the drill string [m]
r_3	wellbore radius [m]
r_1', r_2'	radical radius of formation [m]
T_1	fluid temperatures inside the drill string [°C]
T_2	wall temperature of the drill string [°C]
T_3	annular fluid temperature [°C]
T_4	borehole wall temperature [°C]
T_f	formation temperature [°C]
T_i	inlet temperature [°C]
T_o	outlet temperature [°C]
T_s	surface temperature [°C]
t	time variable [s]
U	overall heat transfer coefficient between the drill string and annulus [W m^{-2} °C^{-1}]
$\vec{V}$	velocity vector of the fluid in the wellbore
z	depth variable [m]

Greek letters

ρ	medium density [kg/m^3]
ρ_f	formation density [kg/m^3]
ρ_m	density of the drilling fluid [kg/m^3]
ρ_w	density of the drill string [kg/m^3]
ρ_4	density of the borehole wall medium (casing/rock) [kg/m^3]
λ	thermal conductivity [W m^{-1} °C^{-1}]
λ_f	thermal conductivity of the formation [W m^{-1} °C^{-1}]
λ_w	thermal conductivity of the drill string [W m^{-1} °C^{-1}]
λ_4	thermal conductivity of the borehole wall (casing/rock) [W m^{-1} °C^{-1}]
λ_5	thermal conductivities of cement sheath/rock [W m^{-1} °C^{-1}]
Φ	heat through the unit area [J/m^2]
α_{ij}, β_{ij}, γ_{ij}, δ_{ij}, and λ_{ij}	matrices coefficients
SOR	Gauss-Seidel iterative method if ω is equal to 1 in the Eq. (29); *SOR* is the over relaxation method if ω is more than 1; *SOR* is the under relaxation method if ω is less than 1

Subscript

1, 2, 3, 4, 5	inside drill string, wall of drill string, annulus, bore-hole, cement sheath/rock, respectively
f	formation
m	drill fluid

deep formation drilling, however, wellbore temperature has a more significant influence than pressure on the properties and density of the wellbore fluid. Karstad et al. investigated the change of fluid density under different conditions, assuming a surface density of 2.04 g/cm^3. The effective density at geothermal conditions is 1.98 g/cm^3. Immediately following the onset of circulation, it increases to 1.99 g/cm^3 and continues to increase to 2.06 g/cm^3 after 12 h of circulation [10]. Madu et al. presented effective density change of high temperature wells in the Niger Delta. It was observed that drilling fluid density decreased with depth, especially at the high temperatures of the hole section, which could give rise to well control issues and stuck pipe incidents [11]. Ataga et al. emphasized the pressure profile in a circulating well, taking into account the temperature profile, to estimate frictional pressure loss, effective density and bottom-hole pressure [12]. If the impact of temperature on effective density is disregarded, there may be disastrous effects. Kick and blow-outs due to under-balanced pressure or lost circulation and formation damage may occur as a result of over-balanced pressure when drilling through formations with a small gap between pore pressure and fracture pressure [9].

Determining the transient temperature distribution in and around a well accurately, under circulation and shut-in conditions, is a complex engineering task because of the dynamic thermal circulation (cooling) and shut-in (heating) processes [13,14]. Many uncertain factors impact the heat exchange between the wellbore and formation, including well geometry, surface temperature, geothermal gradient, fluid inlet temperature, fluid flow rate, fluid properties, continuous circulation of drilling fluid and drilling stoppages [15–17]. To increase the depth of the borehole, high thermal conductivity drill string and casing were used, affecting the heat transfer efficiency in each region of the well. To ensure safe drilling and production, the borehole wall was sealed by casing and cement slurry, which varied the thermal resistance and further impacted heat transfer from formation to wellbore. To facilitate understanding of transient temperature behavior along a wellbore and to inform quick decision making, a reliable and accurate evaluation of temperature distribution requires a complete dynamic thermal study of fluid circulation and stopping circulation in and around the wellbore [18].

Because predicting transient temperature behavior is important, the study of temperature distribution has attracted significant interest. Two approaches have emerged to estimate wellbore temperature: analytical and numerical [19]. The analytical method is derived mainly from constant linear and cylindrical heat source models. Linear heat source models typically consider the analysis of conductive heat flow under radial, cylindrical, or spherical conditions [20]. These methods are widely used to infer the initial formation temperature in the shut-in stage, using the simple solving method. Kutasov et al. estimated geothermal gradients with the approximate method from the log data and identified that duration of the shut-in time was required for more precise evaluation [21]. Verma et al. attempted to predict static formation temperature using the error propagation theory [22]. Garcı́a-Gutierrez et al. calculated effective thermal conductivity of the cement sheath