Development of a New Diagnostic Method for Lost Circulation in Directional Wells

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Abstract: Failure to manage and minimize lost circulation can greatly increase the cost of drilling and the risk of well abandonment. Many lost circulation remedial procedures are not working as planned because the locations of loss zones are incorrectly estimated. The lack of this critical piece of information prevents treatments from being applied directly to the points of losses and, thus, resulting in low efficiency and extended NPT (non-productive time). This paper presents an integrated method for identifying the locations of loss zones with continuous temperature measurement data enabled by drilling microchip technology. A transient thermal model in predicting the temperature profiles in the wellbore and formation during mud loss is developed as a forward calculation procedure of the loss zone mapping method. For a deep well with moderate to severe loss, there are significant changes in the mud circulating temperature profiles as mud loss persists. Certain characteristics of wellbore thermal behavior are evaluated and identified as good indicators of loss zones. Case studies are conducted to demonstrate the practical applications of the method in both onshore and offshore drilling applications. The results from these case studies are important in setting cement plugs, applying expandable tubular systems, and spotting LCM (lost circulation material) pills. Additional uses of this method include identifying highly permeable zones for reservoir or formation evaluation purposes. This method can be used as a routine monitoring process performed regularly without any interference of the drilling operations at the time.

Key words: Lost circulation, thermal modeling, drilling microchip, locating loss zone.

Nomenclature

A_a	Area of annulus cross section, $[L^2]$, m^2	J	Joule's constant, $[L^2 t^{-2} T^{-1}]$, $J/g \cdot ^\circ C$
A_p	Area of drillpipe cross section, $[L^2]$, m^2	k_f	Thermal conductivity of formation, $[M L t^{-3} T^{-1}]$, $W/m K$
c_f	Formation specific heat, $[L^2 t^{-2} T^{-1}]$, $J/g \cdot ^\circ C$	L	Total depth of the well, $[L]$, m
c_{fl}	Pore fluids specific heat, $[L^2 t^{-2} T^{-1}]$, $J/g \cdot ^\circ C$	m	Mass, $[M]$, kg
c_m	Mud specific heat, $[L^2 t^{-2} T^{-1}]$, $J/g \cdot ^\circ C$	$\dot{m}$	Mass flow rate, $[M t^{-1}]$, kg/s
D	Diameter, $[L]$, m	$\dot{m}_a$	Mass flow rate in the annulus, $[M t^{-1}]$, kg/s
g_G	Geothermal gradient in the formation, $[T L^{-1}]$, $^\circ C/m$	$\dot{m}_l$	Mass flow rate of mud loss, $[M t^{-1}]$, kg/s
h_{af}	Convective heat transfer coefficient between annulus fluid and formation, $[M t^{-3} T^{-1}]$, $W/m^2 K$	$\dot{m}_p$	Mass flow rate in the drill pipe, $[M t^{-1}]$, kg/s
h_{ap}	Convective heat transfer coefficient between annulus fluid and formation, $[M t^{-3} T^{-1}]$, $W/m^2 K$	N	Pipe rotation speed, $[t^{-1}]$, RPM
H	Enthalpy, $[M L^2 t^{-2}]$, J	P_{fl}	Pore fluid pressure, $[M L^{-1} t^{-2}]$, Pa
$\hat{H}$	Specific enthalpy, $[L^2 t^{-2}]$, kJ/kg	q	Heat rate, $[M L^2 t^{-3}]$, kW
		$\dot{Q}$	Heat transfer rate, $[M L^2 t^{-3}]$, kW
		$\dot{Q}_{ap}$	Heat transfer rate from drill pipe fluid and the annulus fluid, $[M L^2 t^{-3}]$, kW
		$\dot{Q}_{fa}$	Heat transfer rate from formation to the annulus fluid, $[M L^2 t^{-3}]$, kW
		$\dot{Q}_{hs}$	Rate of heat generation from source, $[M L^2 t^{-3}]$, kW
		r	Radius, $[L]$, m

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s	Measured depth, [L], m
T_a	Annulus fluid temperature, [T], °C
T_{es}	Temperature on the surface, [T], °C
T_i	Initial temperature, [T], °C
T_p	Drillpipe fluid temperature, [T], °C
T_f	Formation fluid temperature, [T], °C
T_w	Temperature of wellbore wall, [T], °C
t	Time, [t], s
U	Overall heat transfer coefficient, [$M t^{-3} T^{-1}$], $W/m^2 K$
u	Specific internal energy, [$L^2 t^{-2}$], J/kg
v	Velocity, [$L t^{-1}$], m/s
V	Volume, [L^3], m^3
z	Vertical depth, [L], m

Greek Letters

α_c	Pressure diffusion constant, [$L^2 t^{-1}$], m^2/s
α_f	Thermal diffusivity, [$L^2 t^{-1}$], m^2/s
Ψ	Internal energy, [$M L^2 t^{-2}$], J
$\hat{\Psi}$	Specific internal energy, [$L^2 t^{-2}$], J/kg
ρ_m	Density of the mud, [$M L^{-3}$], kg/m^3
ρ_f	Density of the formation, [$M L^{-3}$], kg/m^3
ρ_{fl}	Density of the pore fluids, [$M L^{-3}$], kg/m^3

Superscript

U	Upper section
L	Lower section

1. Introduction

Lost circulation is one of the most persistent and costly drilling problems that drilling engineers have been struggling with for decades. Mud loss into natural fractures happens when very porous, cavernous or highly fractured zones intercept the current well path, and the drilling mud losses into this location under the overbalance pressure between the wellbore and formation; while mud loss into induced fractures caused by excessive downhole pressures or setting intermediate casing too high. Lost circulation not only costs large volumes of valuable drilling fluids, it also prevents drilling crews from performing most of their functions.

When conventional treatments do not resolve severe loss problems, spotting LCM (lost circulation

material) pills and holding them under gentle squeeze pressure for a predetermined period may solve the losses: at downhole temperature, LCM pills expand rapidly to fill and bridge fractures, allow drilling and cementing operations to resume quickly. One must know where the loss zones are to spot to the right locations. Furthermore, the overbalance pressure varies with depth, therefore one must have information about the locations of losses to optimize the squeeze pressure and LCM particle size distribution [1].

When severe losses occur, setting cement plugs is an effective way of sealing the loss zones completely. After the plugs are set, one drills back through the plugs or sidetracks the wells. However, without the knowledge of the loss zone locations and the number of loss zones, one cannot determine as what depth to set the cement plugs [2]. Similarly, the evaluation of setting additional casings can be assisted with the information of the number and locations of existing loss zones. Moreover, the information of loss zone locations will be useful when drilling offset wells in an adjacent area.

2. Review of Current Lost Circulation Diagnostic Methods

Logging and other measurements can be used to identify the type of loss and potentially locate thief zones. There are two major categories of methods that can directly assess the locations and sizes of loss zones: fracture diagnostics methods and temperature survey methods, and both of them require stop circulation and perform surveys.

2.1 Fracture Diagnostic Method

Fracture diagnostics methods are essentially performed by logging the target well or offset wells.

A propagation resistivity log is used to find fractures and quantify their dimensions. Two measurements are conducted for this survey: one with high frequency signals, used to provide information about the near

Fig. 1 Deep and shallow resistivity logs in the presence of a short fracture (Lavrov 2016).

well areas—shallow resistivity log; the other one with lower frequency signals, used for deeper formation measurement—deep resistivity log. Electric current induced by the logging tool flows in the circumferential direction around the well. Thus, if a radial fracture is present within the depth of investigation and is filled with high resistivity mud, the measured resistivity will increase. Fig. 1 shows that the discrepancy of the two curves—between deep resistivity log and shallow resistivity log—can indicate the existence of a fractured zone in the immediate vicinity of the well [3, 4]. The other logs that can potentially be used for fracture diagnostics include: image logging, NMR (nuclear magnetic resonance), and microseismic monitoring to obtain information about natural fractures. Unfortunately, image logging and NMR suffer from great practical difficulties to apply during drilling [5, 6]; microseismic monitoring does not work well with the narrow single fracture planes encountered during drilling.

2.2 Temperature Survey

Temperature survey is another method available for locating losses, temperature profile along the open hole is logged several hours after the circulation was stopped. The circulation is then resumed, and the

temperature profile is measured again. The changes (temperature discontinuities) between the two profiles indicate where the mud goes during circulation [7].

In addition to logging, indirect evidence available at the rig can be used to locate the loss zone. For instance, Losses are believed to originate at the drill bit in the following situations: if they are accompanied with a significant change in the rate of penetration, torque, or vibration; if the loss occurs while entering a fractured, vugular, or high-permeability zone known from geological data.

In sum, at present, there is no technique that could be routinely used to directly evaluate lost circulation parameters without stopping circulation and perform surveys. In addition, lost circulation mitigation methods should be performed in a timely manner, the implementation of the above described surveys would greatly hinder this process and cause significant risks. Therefore, this study is aiming to develop a method that could map the loss zones during drilling operation without halting circulation for logging surveys.

3. Application of Continuous Drilling Microchip Measurement in Loss Zone Diagnosis

The ideas of utilizing DTS (distributed temperature system) in flow profiling during production/injection [8] and in the use of fracture-stimulation diagnostics during hydraulic fracturing processes. Seth et al. [9] and Tabatabaei and Zhu [10] have proposed and developed these concepts in the last decade, as commercialized permanent monitoring technologies (such as fiber optic distributed temperature sensors) became available. However, those concepts have yet to be adopted in drilling operations. That is mainly due to the fact that the pressure/temperature profile measurements while drilling are not available with current MWD/LWD (measurement while drilling/logging while drilling) systems which only take measurements close to the bit. It is true even with wired drill pipe, which takes measurements at several

points along the drillbit, but it still does not constitute a continuous measurement along the wellbore.

Drilling microchips “Drilling Tracers” were developed to achieve the continuous pressure and temperature measurement along the wellbore without halting mud circulations [11]. The tracers are initiated and then deployed into the drilling mud, circulate in the wellbore along with the mud while taking measurements with preset frequency. At the end, they are collected in the shale shaker as the mud returns to the surface, as shown in Fig. 2. Measurement data are retrieved through wireless connections between Tracers and data acquisition system. The accuracy of temperature measurement is within $0.56\text{ }^{\circ}\text{C}$. The sampling rate ranges from 0.5-2 Hz and can be adjusted for the specific application. Field tests were conducted in several wells and the concept was successfully validated [12].

The scope of work is to develop a workflow for locating loss zones using distributed temperature measurement. This is achieved by firstly developing a transient wellbore thermal model that can predict the circulating mud temperature profile in the drillpipe and annulus with various mud loss conditions, and then use the characteristics of the altered wellbore thermal behavior to identify the location of mud loss, as illustrated in Fig. 3.

3.1 Mathematical Modeling

Holmes and Swift [13] developed the first analytical model to predict circulating fluid temperature in the drill pipe and annulus, assuming linear steady state heat transfer between formation and annular fluid. Kabir et al. [14] improved this model by considering variable mud inlet temperature as well as backwards circulation operation conditions. Karstad and Aadnoy [15] expanded previous models to handle both an increasing well depth and a variable mud inlet temperature. Most of the early models were analytical and, limited to steady state or pseudo steady state time response. Predicted behaviors at early times under

Fig. 2 Deployment and retrieving process of drilling microchips.

Fig. 3 Wellbore thermal modeling and temperature measurement data interpretation process.

rapidly changing conditions were not accurate, therefore, they cannot model thermal behaviors of the wells during startup and other highly transient operating conditions such as cementing and injection.

Edwardson et al. [16] developed a numerical solution to determine the transient formation temperature disturbance caused by mud circulation. However, the focus of his research is on temperature simulation in the formation, while the mud temperature in the wellbore is used as an input instead of coupling it with formation heat transfer process. Raymond [17] proposed the first numerical model to predict temperature distributions for unsteady and pseudo steady state conditions. This model can be applied to a wide range of wells. However, only conduction is considered for formation heat transmission. Later, Raymond's model was modified to use a different heat transfer correlation and to allow

for multiple casing strings [18]. Nguyen et al. [19] included the effect of frictional heat source from drillstring—wellbore interaction in inclined wellbores and investigated the relative significance of each parameters to the temperature profiles and wellbore failure indices.

Ouyang et al. [8] developed thermal models for single and multiphase fluid flow along vertical or deviated wells, the models were utilized in both wellbore temperature profiles prediction (forward calculation) and flow profiling using a measured temperature profile. Seth et al. [9] developed a forward simulation model to calculate the time dependent temperature profile in the wellbore and surrounding rock during hydraulic fracturing process. Hoang et al. [20] integrated his model with inverse estimation algorithm and developed a new model to estimate both the flow rate in the wellbore and into the fractures using distributed temperature sensing measurement. Davies et al. [21] presented an approach to detect the location of thief zones in a producing well by alternatively producing and shutting in a neighboring well and recording the temperature data in the injection well.

When no mud loss is present, mud flows with a constant flow rate of $\dot{m}_p$ in both flow conduits (drillpipe and annulus). When mud loss occurs, flow rate in the annulus reduces as some of the mud flows into the loss zones. Assuming a uniform area of flow along the axial direction in the annulus, the velocity of mud decreases as it flows through the locations of losses. See Figs. 4 and 5, as the velocity profile changes in the annulus, heat transmission of the system changes. The wellbore is divided into multiple regions in the axial direction, with different governing equations and boundary conditions for each region [22].

In this study, a numerical model for calculating transient mud circulating temperatures in a directional well during mud loss is developed, under the following assumptions:

Fig. 4 Schematic of flow rate distribution in an example well with multiple loss zones.

Fig. 5 Schematic of energy balance in a control volume.

- Mud temperature is uniform across the area of flow in the drill pipe or annulus for a given depth.
- Viscous dissipation-induced heat is negligible.
- Concentration of solids in the mud is homogeneous.
- Filtration effect is negligible.
- Heat generated from friction between drillstring and wellbore is evenly distributed.

When modeling inclined boreholes, the mass and energy balance equation is established on the basis of measured depth; therefore, the governing equations obtained from vertical wells must be modified accordingly. Besides, in deviated wells, the drill pipes are usually in direct contact with borehole wall, especially in high dogleg sections, creating friction between the components. Therefore, heat generated by mechanical friction based on a drag and torque model are added in to the calculation for a more realistic prediction. The enthalpy and heat transfer rate terms in the government equation are given as

$$\sum_{k=1}^M \dot{m}_k \hat{H}_k = \dot{m}_a \left(c_v (T(s + \Delta s) - T(s)) + \frac{P(s + \Delta s) - P(s)}{\rho} \right) \quad (1)$$

$$\begin{aligned} \sum_{j=1}^N \dot{Q}_j &= \dot{Q}_{fa}(s, t) + \dot{Q}_{hs}(s, t) - \dot{Q}_{ap}(s, t) \\ &= 2\pi r_w \Delta s h_{af} (T_w - T_a) \\ &\quad + \frac{1}{J} \int_{s_1}^{s_2} \mu_f w_c r_p 2\pi N ds \\ &\quad - 2\pi r_p \Delta s U_{ap} (T_a - T_p) \end{aligned} \quad (2)$$

Base on energy balance in the control volume illustrated in Fig. 5, the equilibrium can be expressed as

$$\begin{aligned} c_m m dT &= \dot{m}_a \left(\hat{\Psi}(s + \Delta s) + \frac{P(s + \Delta s)}{\rho} \right) \\ &- \dot{m}_a \left(\hat{\Psi}(s) + \frac{P(s)}{\rho} \right) + \dot{Q}_{fa}(s, t) + \dot{Q}_{hs}(s, t) \\ &- \dot{Q}_{ap}(s, t) \end{aligned} \quad (3)$$

Eq. (3) can be expanded into

$$\begin{aligned} \frac{c_v \rho_m A_a \Delta s dT}{dt} &= \dot{m}_a (c_v (T(s + \Delta s) - T(s))) \\ &\quad + 2\pi r_w \Delta s h_{af} (T_w - T_a^U) \\ &\quad + \frac{1}{J} \int_{s_1}^{s_2} \mu_f w_c r_p 2\pi N ds \\ &\quad - 2\pi r_p \Delta s U_{ap} (T_a - T_p) \\ \frac{\rho_m c_m A_a}{2\pi r_w h_{af}} \frac{\partial T_a}{\partial t} &= \frac{c_m \dot{m}_a}{2\pi r_w h_{af}} \frac{\partial T_a}{\partial s} - (T_a - T_w) \\ &\quad + \frac{\mu_f w_c(s, t) r_p N}{J r_w h_{af}} \\ &\quad + \frac{r_p U_{ap}}{r_w h_{af}} (T_p - T_a) \end{aligned} \quad (4)$$

The annulus is divided into multiple segments by different local flow rates as a result of mud losses

$$\begin{aligned} \frac{\rho_m c_m A_a}{2\pi r_w h_{af}^1} \frac{\partial T_a^1}{\partial t} &= \frac{c_m \dot{m}_a^1}{2\pi r_w h_{af}^1} \frac{\partial T_a^1}{\partial s} - (T_a^1 - T_w) \\ &\quad + \frac{\mu_f w_c(s, t) r_p N}{J r_w h_{af}^1} \\ &\quad + \frac{r_p U_{ap}^1}{r_w h_{af}^1} (T_p - T_a^1) \end{aligned} \quad (5)$$

$$\begin{aligned} \frac{\rho_m c_m A_a}{2\pi r_w h_{af}^i} \frac{\partial T_a^i}{\partial t} &= \frac{c_m \dot{m}_a^i}{2\pi r_w h_{af}^i} \frac{\partial T_a^i}{\partial s} - (T_a^i - T_w) \\ &\quad + \frac{\mu_f w_c(s, t) r_p N}{J r_w h_{af}^i} \\ &\quad + \frac{r_p U_{ap}^i}{r_w h_{af}^i} (T_p - T_a^i) \\ \frac{\rho_m c_m A_a}{2\pi r_w h_{af}^N} \frac{\partial T_a^N}{\partial t} &= \frac{c_m \dot{m}_a^N}{2\pi r_w h_{af}^N} \frac{\partial T_a^N}{\partial s} - (T_a^N - T_w) \\ &\quad + \frac{\mu_f w_c(s, t) r_p N}{J r_w h_{af}^N} \\ &\quad + \frac{r_p U_{ap}^N}{r_w h_{af}^N} (T_p - T_a^N) \end{aligned}$$

Meanwhile the governing equation for transient drill pipe mud temperature can be represented as

$$\frac{\rho_m c_m A_p}{2\pi r_p U_{ap}} \frac{\partial T_p}{\partial t} = - \frac{\dot{m}_p c_m}{2\pi r_p U_{ap}} \frac{\partial T_p}{\partial s} + (T_a - T_p) \quad (7)$$

Heat transfer between annulus mud and the formation through the wellbore wall is represented by

$$\begin{aligned} 2\pi r_w h_{af} (T_f(s, r_w, t) - T_a) \\ = 2\pi r_w k_f \frac{\partial T_f(z, r_w, t)}{\partial r} \end{aligned} \quad (8)$$

Coupled pressure and heat diffusion processes in the formation can be represented by Eqs. (9) and (10) [19]:

$$\begin{aligned} \frac{\partial T_f(s, r, t)}{\partial t} \\ = \alpha_f \left(\frac{\partial^2 T_f(s, r, t)}{\partial r^2} + \frac{1}{r} \frac{\partial T_f(s, r, t)}{\partial r} \right) \\ + \frac{\rho_{fl} c_{fl}}{\rho_f c_f} \frac{\partial P_f(s, r, t)}{\partial r} \frac{\partial T_f(s, r, t)}{\partial r} \end{aligned} \quad (9)$$

$$\begin{aligned} \frac{\partial P_f(s, r, t)}{\partial t} &= \alpha_c \left[\left(\frac{\partial^2 P_f(s, r, t)}{\partial r^2} \right. \right. \\ &\quad \left. \left. + \frac{1}{r} \frac{\partial P_f(s, r, t)}{\partial r} \right) \right. \\ &\quad \left. + c_{fl} \left(\frac{\partial P_f(s, r, t)}{\partial r} \right)^2 \right] \end{aligned} \quad (10)$$

where,

$$\alpha_c = \frac{\kappa_f}{\mu_{fi} \phi^2 C_i}$$

3.2 Application for Vertical Wells with Single Loss Zone

3.2.1 Application in Onshore Wells

Consider a vertical well drilled at 4,572 m. The base case input parameters are presented in Table 1. Initial temperature distribution in the formation is assumed to be linear with a constant of 0.033 °C/m. Steady-state shut-in temperature of the wellbore is considered to be the same as the original formation temperature.

Under most circumstances, mud loss occurs during the rig state of drilling, which means the temperature profiles prior to the mud loss are usually in a near steady-state condition with sufficient mud circulation. To establish this condition, we assume an initial shut-in temperature profile for both the drilling fluid and the formation. Then start circulation without mud loss for 24 Hrs. By the end of this time interval, the temperatures in the wellbore start to change at much slower rates. Mud loss is introduced to the system by the end of the 24th hour, and the initial conditions for the simulation are the temperature profiles at this time stamp. To better represent the scale of loss, the concept of dimensionless loss rate λ is introduced, which is defined as the ratio between loss rate and pump rate.

Fig. 6 shows that, the rates of temperature changes are most significant in the early stage of mud loss (the first 8 Hrs. compares to the rest), and eases as time goes. It is tempting to assume one could directly use the mud return temperature on the surface to evaluate the location and extend of loss, however, according to the simulation results, the location of loss has very little effect on the annular mud temperature at surface, i.e. the temperature of return mud. Although the annular mud temperature at surface does not change much regardless of mud loss conditions after long circulation, at the lower sections of the well, the reduction in annular mud temperature is significant and therefore cannot be ignored.

Sensitivity analyses are conducted to evaluate the effects of loss rate and location of loss on annular mud

Table 1 Base case input data to simulate downhole transport progress.

Parameters	Descriptions and units	Values
D_p	Drill stem OD (m)	0.1683
D_w	Drill bit size (m)	0.2127
q_p	Inlet volumetric flow rate (m ³ /s)	0.019
ρ_m	Mud density (kg/m ³)	1,438
T_{in}	Inlet mud temperature (°C)	23.9
μ_m	Mud viscosity (kg/m s)	0.046
K_m	Mud thermal conductivity (W/m K)	0.6
K_s	Steel pipe thermal conductivity (W/m K)	50
K_f	Formation thermal conductivity (W/m K)	1.3
c_m	Mud specific heat (KJ/K kg)	1.672
c_f	Formation specific heat (kJ/K kg)	0.836
c_{fl}	Pore fluids specific heat (kJ/K kg)	2.09
ρ_f	Formation density (kg/m ³)	2,640
T_{es}	Surface earth temperature (°F)	15.6
g_G	Geothermal gradient (°C/m)	0.0328
α_f	Formation thermal diffusivity (m ² /s)	1.15E-06

Fig. 6 Annular mud temperature at different locations of the well during mud loss (loss occurred at 4,115 m, $\lambda = 25\%$).

temperature. Fig. 7 illustrates the effect of loss rate on mud temperature reduction in annulus after 24 Hrs. of circulation. According to the results, the amount of temperature reduction increases as the loss rate increases. Fig. 8 shows the effect of mud loss location on the reduction of annular mud temperature after 24 Hrs.

Fig. 7 Annular mud temperature reduction at different locations of the well after 24 Hrs. of mud loss ($\lambda = 10\%$, 30% , and 50%).

Fig. 8 Annular mud temperature reduction at different locations of the well after 12 Hrs. of loss (location of loss at 3,200 m, 3,810 m, and 4,420 m).

of circulation. With constant pump rates and mud loss rates, the deeper of the loss, the more reduction in annular mud temperature within the same amount of time.

The change in temperature profiles of tubular muds in the wellbore is affected by many parameters. Some of them are lost circulation conditions related, while some of them are associated with the thermal properties of mud and formations, and the latter are mostly uncertain. Therefore, temperature predictions with constant loss rate assumptions could be inaccurate. Thus, the direct use of these characteristic curves to predict the location of a loss zone would be improper. On the other hand, although the temperature profile values themselves cannot be used as an effective indicator of loss zone, by taking the derivative of mud temperature with respect to depth, the resulting curves could be used to identify the location of loss zones in a more effective manner. During 24 Hrs. of mud loss, the alteration in heat transfer profile induces an additional decrease in the $\partial T_p / \partial s$ value for upper sections in the wellbore, as shown in Fig. 9. Similar behavior is demonstrated in $\partial T_a / \partial s$ curves, except at the location of mud loss, a significant jump on the curve is observed upon occurrence of mud loss, as shown in Fig. 10. The break point in the $\partial T_a / \partial s$ curve indicates the discontinuity of flow rate and therefore coincide with the location of loss zone, and can be used to effectively identify the location of mud loss.

Fig. 9 Depth derivative of drillpipe mud temperature over time with loss.

Fig. 10 Depth derivative of annular mud temperature over time with loss.

3.2.2 Application in Offshore Wells

Fluid loss is of primary concern when drilling offshore wells, since lost circulation is exacerbated in these drilling applications. The overpressure and low horizontal stresses may significantly reduce the operational BHP (bottom hole pressure) window in deepwater wells. In addition to the narrow operation window, the use of riser will also increase the chance of mud loss at locations other than the bottom of the well. Overbalanced drilling of the shallow sediment with a riser will result in the static BHP profile shown by the dotted line in Fig. 11. It is evident that keeping the BHP above the pore pressure in the lower part of the open hole will bring the annular pressure above the fracturing pressure higher up the hole. This induces losses in the upper part of the hole. Therefore during offshore operations, it is more risky to take the default answer and assume the loss occurs at the bottom of the well.

The heat transfer scenario in an offshore well is significantly different from that in an onshore well. The proposed model in preceding subsection is reformulated for an offshore well drilling application and the details are given in Appendix.

Fig. 11 Pore pressure and fracturing pressure versus depth in marine drilling with riser.

Consider a vertical offshore well drilled at 1,524 m of water depth, with a total measured depth of 5,487 m. The initial temperature profile in seawater is defined in Appendix (5), and the rest of the inputs follow those in the base case. Similar to the vertical single loss zone model, initial conditions are established by shut-in temperature profiles followed by circulation without mud loss for 24 hours.

Comprehensive sensitivity analysis was performed on $\partial T_a / \partial z$ at various loss rates, loss zone locations and other mud loss conditions, to evaluate the characteristics in $\partial T_a / \partial z$ curves induced by different mud loss scenarios. Fig. 12 illustrates the $\partial T_a / \partial z$ profiles at various loss zone depths. In this study, the location of loss zone is varied, while the loss rate is kept constant. Other parameters are the same as the base-case inputs. Note that the locations of break points in the curve coincide with the locations of loss (4,115 m, 4,572 m, 5,300 m respectively). Fig. 13 shows the effect of loss rate on the $\partial T_a / \partial z$ profile. As the loss rate increases, the jump at the discontinuity gets magnified.

Furthermore, the closer the loss zone to the maximum temperature location ($\partial T_a / \partial z = 0$), the

Fig. 12 Effect of loss zone location on depth derivative of annular mud temperature.

Fig. 13 Effect of dimensionless mud loss rate on depth derivative of annular temperature.

smaller the jump at the break point in the derivative plot. In the case when the derivative occurs at the location of maximum temperature, one needs additional information to identify the location of loss.

The examples given above assume a constant mud loss rate, however, under most circumstances, mud loss rate is inconsistent and changes over time. In this example, a spurt loss occurred at $t = 12 \text{ hr}$ with $\lambda = 25\%$ and reduced to a seepage loss ($\lambda = 1\%$) after 2 hours, then maintained at the same loss rate for the next 8 hours. After 8 hours, the well relapsed to a

severe loss with $\lambda = 25\%$. The dimensionless loss rate as a function of time is illustrated in Fig. 14. The simulation results of $\partial T_a / \partial z$ vs z are presented in Fig. 15. During the stage of seepage loss, the loss rate was too low to induce any observable break point in the derivative curve. However, as soon as the mud loss was reinitiated, the discontinuity in the derivative reappeared in a few minutes. Therefore, in a field application, as long as there is sufficient mud loss at the time of temperature measurement, the discontinuity in the derivative can be captured regardless of the mud loss history during the entire drilling process.

Fig. 14 Variable mud loss rates over time.

Fig. 15 Depth derivative of annular mud temperature with variable loss rates.

3.3 Deviated Well with Multiple Loss Zones

Lost circulation is more likely to occur and in a more severe form in deviated and horizontal wells due to the following reasons: Increased stress anisotropy; increased frictional pressure loss in the annulus as the well becomes longer; poor hole cleaning. In addition, when drilling long openhole sections, e.g. in extended reach wells, mud losses could occur simultaneously at multiple locations. The identification of the distribution of losses in these wells can facilitate a more efficient and effective lost circulation management process.

Table 2 shows the survey data of an example directional well. Similar to the results obtained from vertical wells, a break point in $\partial T_a / \partial s$ is observed at the location of mud loss, even though the loss occurs at the horizontal section. Meanwhile, mud loss induces a kink in the curve of $\partial T_a / \partial s$ at the location of loss, which is indicative but less substantial in terms of identifying loss zone location. Consider mud is lost into two thief zones with a loss rate of $\lambda = 10\%$ into each zone, the depths of the loss zones are assumed to be 4,359 m and 5,090 m respectively, with one located at the build section and the other one at the horizontal section.

Fig. 16 shows the characteristics in the annular mud temperature derivative curves are consistent with the vertical case, in spite of nonlinear initial temperature distribution in the axial direction, i.e., the locations of break points in derivative curve coincide with the mud loss locations regardless of different inclination angles.

Table 2 Survey Data of the Example Directional Well.

MD (m)	Inclination (°)	TVD (m)	North (m)	Dogleg severity (°/100 m)
0	0	0	0	
3,657	0	3,658	0	0
3,962	19.1	3,957	50	6.27
4,267	38.2	4,223	196	6.27
4,572	57.3	4,427	420	6.27
4,876	76.4	4,546	700	6.27
5,181	90	4,572	1,000	0
6,096	90	4,572	1,916	0

Since the mud losses are now coming from separate loss zones, the magnitude of the leap in $\partial T_a / \partial s$ for each zone is less significant than the one when the totaled mud loss is into one single location. Fig. 17 illustrates that the behaviors of the drill pipe temperature derivative are similar to those in the case

Fig. 16 Depth derivative of annular mud temperature over time in a directional well with multiple loss zones.

Fig. 17 Depth derivative of drill pipe mud temperature over time in a directional well with multiple loss zones.

study with a vertical well; i.e., the kinks in $\partial T_p / \partial s$ curve are not affected by the inclination angle.

The comparison of the annular temperature derivative curves prior and after mud losses reveals that different mud loss distributions (with multiple loss zones) create different mud temperature derivative profiles in the wellbore, which can be used to quantify the fluid placement. In addition to loss zone locations determinations, the case studies demonstrated above suggest that, visual interpretation of data can help us in identifying the scale of fluid loss at each location and potentially be used for characterizing the nature of fluid loss, i.e., loss into natural fractures/fractured zones, induced fractures, high permeable zones, etc., at each location when combining the results from this method with other geophysics and petrophysics data.

4. Conclusions

A new method of mapping loss zones in directional wells using continuous temperature measurements is developed. Transient mud circulating temperature with multiple loss zones is modeled as a forward calculation process of the workflow. The model has also been reformulated for offshore drilling applications. Comprehensive sensitivity analyses are conducted in characterizing effects of lost circulation related parameters on the circulating mud temperature profiles in drill pipe and annulus.

Mud loss induces additional temperature reductions in both drill pipe and annulus, which is affected by factors such as rates and locations of losses. Comparing to mud circulating temperature profile, the depth derivative of annular mud temperature serves as a better indicator of loss zone locations. By identifying the number and locations of break points in the plot of depth derivative of annular mud temperature, one could identify the locations of losses. The break points in the curve are affected by lost circulation related parameters: loss rate, location of loss, duration of loss, number of loss zones, etc.

Inclination angle has little effect on the break points in the derivative curve, in spite of their effects on the absolute mud circulating temperature values. In addition to loss zone locations determinations, the case studies suggest that, the interpretation of data can help us in identifying the scale of fluid loss at each location and potentially be used for characterizing the nature of fluid loss when used together with other petrophysics data. This new method focuses on the effect of flow variation in the wellbore during mud loss on the redistribution of mud temperature, therefore serves as the most direct method to identify and quantify the losses comparing to the methods through characterizing subsurface fractures.

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SI Metric Conversion Factors

bbl × 1.589 873	E-01 = m ³
Btu × 1.055 056	E+00 = kJ
cp × 1.0*	E-03 = Pa·s
ft × 3.048*	E-01 = m
(°F-32)/1.8	E+00 = °C
gal × 3.785 412	E-03 = m ³
in. × 2.54*	E+00 = cm
lbf × 4.448 222	E+00 = N
lbm × 4.535 924	E-01 = kg
psi × 6.894 757	E+00 = kPa

*Conversion factor is exact.

Appendix

In order to represent downhole heat transfer scenario in an offshore well, the wellbore is divided into three regions in the axial direction, with different flow conditions and geometries in each region. Region I includes all sections above the seabed; Region II includes the sections between the seabed and the point of loss; and Region III includes the sections below the point of loss.

Drillpipe (Region I, II, III): Applying heat balance to the drillpipe fluids yields

$$\frac{\rho_m c_m A_p}{2\pi r_p U_{ap}} \frac{\partial T_p}{\partial t} = -\frac{\dot{m}_p c_m}{2\pi r_p U_{ap}} \frac{\partial T_p}{\partial z} + (T_a - T_p) \quad (1)$$

Assuming temperature profiles are continuous at the loss zone one obtain

$$T_a^U(z = z_f, t) = T_a^L(z = z_f, t) \quad (2)$$

$$T_p^U(z = z_f, t) = T_p^L(z = z_f, t) \quad (3)$$

Riser Heat Transfer (Region I):

$$\dot{Q}_{ar} = 2\pi r_{ro}^R \Delta z h_{ar}^R (T_{ro} - T_a^R) \quad (4)$$

T_{ro} in (4) is defined as the surface temperature of the thermal boundary layer outside the riser, which is assumed to be the original seawater temperature distribution.

$$T_{ro} = T_i^R(z) = \begin{cases} 5 * 10^{-6} z^2 - 0.0201z + 59.945, & 0 \leq z \leq 3000 \\ 40, & 3000 < z \leq 5000 \end{cases} \quad (5)$$

Annulus Fluid (Region I): For the sections above the seabed, the flow rate remains as $\dot{m}_a^U$, however, the flowing area increases to A_a^R , the forced convective heat transfer coefficient between the annular mud and the riser changes to h_{ar}^R , which yield

$$\frac{\rho_m c_m A_a^R}{2\pi r_w^R h_{ar}^R} \frac{\partial T_a^R(z, t)}{\partial t} = \frac{c_m \dot{m}_a^U}{2\pi r_w^R h_{ar}^R} \frac{\partial T_a^R(z, t)}{\partial z} - (T_a^R - T_w) + \frac{r_p U_{ap}}{r_w^R h_{ar}^R} (T_p - T_a^R) \quad (6)$$

Annulus Fluid (Region II): Similarly, for the sections above the point of loss, since the flow rate reduces from $\dot{m}_a^L$ to $\dot{m}_a^U$, the energy balance equation becomes

$$c_m \rho_m A_a \Delta z \frac{\partial T_a^U(z)}{\partial t} = c_m \dot{m}_a^U T_a^U(z + \Delta z, t) - c_m \dot{m}_a^U T_a^U(z, t) + 2\pi r_w \Delta z h_{af} (T_w - T_a^U) - 2\pi r_p \Delta z U_{ap} (T_a^U - T_p) \quad (7)$$

Which yields

$$\frac{\rho_m c_m A_a}{2\pi r_w h_{af}} \frac{\partial T_a^U(z, t)}{\partial t} = \frac{c_m \dot{m}_a^U}{2\pi r_w h_{af}} \frac{\partial T_a^U(z, t)}{\partial z} - (T_a^U - T_w) + \frac{r_p U_{ap}}{r_w h_{af}} (T_p - T_a^U) \quad (8)$$

Annulus Fluid (Region III): For the sections below the point of loss, where the mud flow rate $\dot{m}_a^L$ is assumed to be the original mud inlet flow rate, $\dot{m}_p$,

$$\frac{\rho_m c_m A_a}{2\pi r_w h_{af}} \frac{\partial T_a^L(z, t)}{\partial t} = \frac{c_m \dot{m}_a^L}{2\pi r_w h_{af}} \frac{\partial T_a^L(z, t)}{\partial z} - (T_a^L - T_w) + \frac{r_p U_{ap}}{r_w h_{af}} (T_p - T_a^L) \quad (9)$$