Prediction of Hydrostatic Pressure and Downhole Mud Temperatures While Drilling

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Abstract: In deep and hot wells, the densities of water/oil muds and brines (geofluids) can be significantly different from those measured at surface conditions. As a result, bottom-hole pressures predicted with constant mud densities can be in error by hundreds of psig. Determining accurate the density of drilling mud (the density of the formation fluids) under downhole conditions needs for calculating the actual hydrostatic pressure in a well and predicting differential pressure at the bottom-hole. This will help to reduce the fluid losses resulting from miscalculated pressure differentials. In areas with high geothermal gradients, the thermal expansion of drilling muds can lead to unintentional underbalance, and a kick may occur. In this paper we demonstrate the use of an empirical equation for the downhole circulating mud temperature as well as the early derived analytical equation for the drilling mud hydrostatic pressure. A field example is presented.

Keywords: Drilling fluids, deep wells, bottom hole temperature, hydrostatic pressure, circulating temperature.

1. INTRODUCTION

A lot of unique geological-geophysical information is obtained during the borehole drilling. However, the drilling is always accompanied by different disturbing processes and their precise calculation is an actual physical-mathematical problem.

Accurate prediction of bottom hole circulating temperatures is important during drilling and completion of a well and is critical to properly design a cement slurry. Downhole temperature is an important factor affecting the thickening time of cement, rheological properties, compressive strength development, and set time. The American Petroleum Institute (API), Sub-committee 10 (Well Cements) has developed new temperature correlations for estimating circulating temperatures for cementing [1, 2]. To use the current API bottom hole temperature circulation correlations (schedules) for designing the thickening time of cement slurries (for a given depth) the knowledge of the averaged static temperature gradient is required. The surface formation temperature (SFT) for the current API test schedules is assumed to be 80°F. Earlier we developed a simple method, which allows to use the API temperature correlations for any values of SFT [3].

Below the use of an empirical formula is suggested for estimation the downhole mud circulating temperature.

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In deep and hot wells, the densities of water/oil based muds (geofluids) can be significantly different from those measured at surface conditions (and different from the natural environments) [e.g., 4]. Calculations have shown that bottom hole pressures predicted with constant surface densities to be in error by hundreds of psi. Determining accurate density of drilling mud under downhole conditions is therefore needed for calculating the actual hydrostatic pressure in a well. This will permit a more accurate prediction of differential pressure at the bottom hole and will help to reduce the fluid losses resulting from miscalculated pressure differentials. In areas with high geothermal gradients, the thermal expansion of drilling muds can lead to unintentional underbalance, and a kick may occur. Earlier we suggested formulas which allow one to determine the downhole hydrostatic pressure [5-8].

In this paper we will assume that the well is drilled in a new area and the geothermal profile is not known. From economical considerations is also clear that all input data should be obtained from temperature logs while drilling. Below we present an example which demonstrates the utilization of proposed formulas while drilling.

2. CIRCULATING MUD TEMPERATURE

Let us now assume that the static temperature gradient cannot be determined ted with a sufficient accuracy. In this case, only empirical methods can be used to estimate the downhole circulating temperatures [5, 7, 9, 10]. The temperature surveys in many deep wells have shown that both the outlet drilling fluid

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temperature [4, 11] and the bottom hole temperature varies monotonically with the vertical depth [6, 12]. It was suggested that the stabilized circulating fluid temperature in the annulus (T_m) at any point can be expressed as [13]:

$$T_{\mathrm{m}} = C_0 + C_1 h + C_2 H, \quad h \le H,$$

where C_0, C_1, and C_2 are the empirical coefficients; h is the current depth, and H is the total vertical depth.

The values of C_0, C_1, and C_2 are dependent on drilling technology (flow rate, well design, mud properties, penetration rate) geothermal gradient and thermal properties of formations. It is assumed that, for a given area, the above mentioned parameters vary within narrow limits.

For offshore wells the Eq. (1) should be modified:

$$T_m = C_0 + C_1\left(h - D_R\right) + C_2\left(H - D_R\right), \quad D_R \le h \le H, \quad (1)$$

where D_R is the length of the riser.

The determination of the coefficients C_0, C_1, and C_2 for deep-water wells is more complicated. In this case computer models can be used to determine the “outlet mud temperature” (at $h = D_R$) from the recorded values of T_{out} (at h = 0). In order to obtain values of C_o, C_1, and C_2, the records of outlet mud temperature (at h = 0) and results of downhole surveys are needed. In Eq. (1) the value of T_{m} is the stabilized downhole circulating temperature. The time of the downhole temperature stabilization can be estimated from the routinely recorded outlet mud temperature (T_{out}) logs. Recording the values of the outlet mud temperature in time during mud circulation without penetration we can determine the moment of time after which the value of T_{out} is practically constant. Eq. (1) was verified with more than 10 deep wells and the results were satisfactory [14]. The advantage of Eq. (1) is that the temperature surveys in several wellbores drilled in the same area can be utilized in determining the empirical coefficients [14].

3. HYDROSTATIC PRESSURE

Earlier we developed an empirical equation of state (pressure-density-temperature dependence) for drilling muds and brines [15]:

$$\rho = \rho_0 \exp\left[\alpha p + \beta\left(T - T_s\right) + \gamma\left(T - T_s\right)^2\right], \quad (2)$$

where T is the temperature ($^{\circ}$F); p is the pressure, psig; T_s = 59°F = 15°C (International standard temperature); ρ is the fluid density, ppg; ρ_0 is the fluid density (ppg) at standard conditions (p = 0 psig, T = 59°F.); á (isothermal compressibility), β and γ are constants.

Let us assume that the stabilized circulating mud temperature is a linear function of the vertical depth

$$T = T_m = a_0 + a_1 h, \quad (3)$$

then the bottomhole and outlet stabilized circulating mud temperatures are:

$$T_{\mathrm{bot}} = T_{\mathrm{out}} + a_1 H, \quad T_{\mathrm{out}} = a_0, \quad a_1 = \frac{T_{\mathrm{bot}} - T_{\mathrm{out}}}{H}. \quad (4)$$

Using Eqs. (2) and (3) we obtained a general equation for determining the downhole hydrostatic pressure [5, 6]:

$$p = \frac{1}{\alpha} - \sqrt{\frac{1}{\alpha^2} - \frac{2F}{\alpha}}, \quad (5)$$

where,

$$F = B_0\left(B_1 B_2 - A_0\right), \quad (6)$$

$$A_0 = 1 + \gamma\left[\left(a_0 - T_s\right)^2 - \frac{2}{\beta}\left(a_0 - T_s\right) + \frac{2}{\beta^2}\right], \quad (7)$$

$$B_0 = \frac{\rho_0 g}{a_1 \beta} \exp\left[\beta\left(a_0 - T_s\right)\right], \quad (8)$$

$$B_1 = \exp\left(\beta a_1 h\right), \quad (9)$$

$$B_2 = 1 + \gamma\left[\left(a_0 + a_1 h - T_s\right)^2 - \frac{2}{\beta}\left(a_0 + a_1 h - T_s\right) + \frac{2}{\beta^2}\right], \quad (10)$$

Example: A major oil company took extensive circulating temperature data while drilling and completing a deep Mississippi well [16]. The stabilized values of bottomhole circulating temperature were measured while drilling at H = 16,079 ft, H =21,439 ft, and H = 23,669 ft. The outlet mud temperature (at h = 0) was also recorded. The actual outlet (flowline) and bottomhole temperatures recorded during logging are presented in Table **1**. From plots of outlet mud temperature versus time the values of stabilization time (t_s) were obtained [14, 16]:

$$t_s = 0.77 + 1.45 \cdot 10^{-4} H, \quad (11)$$

where time t_s is given in hours and depth H in ft.

Three measurements of stabilized bottomhole circulating temperatures and three values of stabilized outlet mud temperatures were run in a multiple regression analysis computer program and the coefficients of the empirical Eq. (1) were obtained:

$C_0 = 90.82\ ^{\circ}\mathrm{F}$, $C_1 = 0.00924\ ^{\circ}\mathrm{F}/\mathrm{ft}$, $C_2 = 0.001728\ ^{\circ}\mathrm{F}/\mathrm{ft}$.

Thus, the equation for the downhole circulating temperature is:

$$T_m = 90.82 + 0.00924h + 0.001728H, \quad h \le H. \tag{12}$$

We compared the measured and calculated (Eq. (12)) values of the bottomhole and outlet circulating temperature (Table **1**). As one can see the measured and predicted values are in a satisfactory agreement. From the last equation follows that:

$$T_{\mathrm{bot}} = 90.82 + (0.00924 + 0.001728) H = 90.82 + 0.010968H, \tag{13}$$

$$T_{\mathrm{out}} = 90.82 + 0.001728H. \tag{14}$$

The gradient of the mud circulating temperature is:

$$a_1 = \frac{(T_{\mathrm{bot}} - T_{\mathrm{out}})}{H} = C_1 = 0.00924\,^{\circ}\mathrm{F/ft}. \tag{15}$$

Downhole drilling mud temperatures for three values of the total vertical depths are presented in Table **2.**

Let us assume that a water base mud was used with the following parameters [15, 17], Eq. (2):

ρ_0 = 18.079 ppg, α = 3.0296·10^{-6} 1/psig,

Table 1: Measured (T_m*) and Predicted (T_m) Values of Downhole mud Circulating Temperature

h, ft	*H*, ft	T_m*, °F	T_m, °F	T_m*- T_m, °F
16,079	16,079	265.0	267.3	-2.3
21.439	21,439	325.0	326.1	-1.1
23,669	23,669	353.0	350.6	2.4
0	16,079	122.0	118.6	3.4
0	21.439	125.0	125.6	-0.6
0	23,669	132.0	131.7	0.3

Table 2: Downhole Drilling mud Temperature, °F

h, ft	Total Vertical Depth, ft				
	8,000	**12,000**	**16,079**	**21,439**	**23,669**
0	104.6	111.6	118.6	127.9	131.7
2,000	123.1	130.0	137.1	146.3	150.2
4,000	141.6	148.5	155.6	164.8	168.7
6,000	160.1	167.0	174.0	183.3	187.2
8,000	178.6	185.5	192.5	201.8	205.6
10,000		204.0	211.0	220.3	224.1
12,000		222.4	229.5	238.7	242.6
14,000			248.0	257.2	261.1
16,079			267.2	276.4	280.3
21,439				326.0	329.8
23,669					350.4

Table 3: Calculated Hydrostatic Pressure

h, ft	Total Vertical Depth, ft					
	23,669		21,439		16,079	
	p, psig	*p* - *p**, psig	*p*, psig	*p* - *p**, psig	*p*, psig	*p* - *p** psig
2,000	1859	-20	1857	-22	1864	-14
4,000	3722	-34	3718	-38	3728	-28
6,000	5582	-53	5588	-47	5600	-35
8,000	7447	-66	7454	-60	7470	-43
10,000	9317	-75	9324	-67	9343	-48
12,000	11186	-84	11194	-76	11221	-49
14,000	13057	-91	13066	-82	13098	-50
16,079	14999	-102	15015	-86	15049	-51
21,439	20012	-123	20031	-104		
23,669	22097	-132				

$\beta = -1.3547\cdot 10^{-4}$ 1/^{o}F, $\gamma = -4.1444\cdot 10^{-7}$ 1/^{o}F^2.

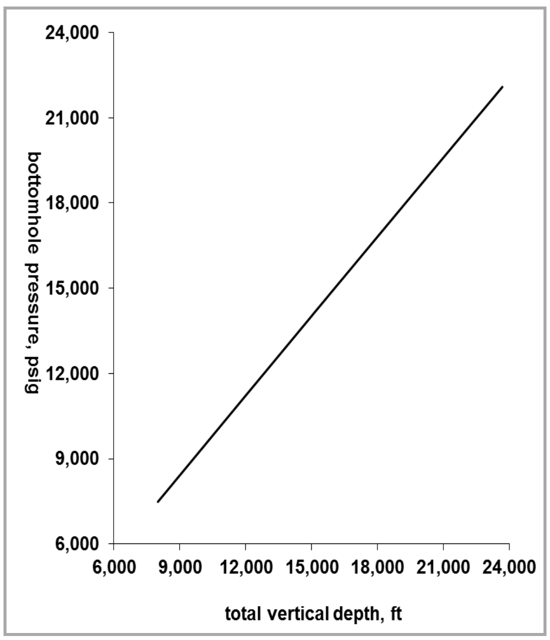

Figure 1: Bottom hole hydrostatic pressure.

The results of calculations after Eqs. (5-15) are presented in Table **3** and Figure **1**. We also compared values of hydrostatic pressure (Eq. (10)) with those (p^*) calculated by the conventional constant-surface-mud-density method:

$$p^* = B_c \rho_0 h, \qquad B_c = 0.052 \frac{\text{psi}}{\text{ppg} \cdot \text{ft}}. \qquad (16)$$

As follows from Table **3** the effect of the temperature and pressure on drilling mud density should be taken into account at downhole mud pressure predictions. Thus the determination of the coefficients in Eq. (1) allows one to forecast the downhole circulating mud temperatures and to calculate hydrostatic pressures while drilling.

The suggested methodology will be evaluated at the thermal data from several hydrocarbon boreholes of Azerbaijan.

CONCLUSIONS

It is shown that the effect of the temperature and pressure on drilling mud density should be taken into account at downhole mud pressure predictions. The corresponding methodology of calculation this effect is presented. Application of the presented equations will allow to obtain more exact values for downhole circulating mud temperatures and hydrostatic pressures in petroleum industry.

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NOMENCLATURE

A_0 = Function

a_0, a_1 = Coefficients

B_0, B_1, B_2 = Functions

C_0, C_1, C_2 = Empirical coefficients

D_R = Length of the riser

F = Function

g = Gravity acceleration

H = Total vertical depth

h = Vertical depth

p = Pressure

p^* = Pressure at constant fluid density($\rho=\rho_0$)

T = Temperature

T_s = 15°C, International standard temperature

T_{out} = Stabilized outlet mud temperature

T_{bot} = Stabilized bottomhole mud temperature

T_m = Mud circulating temperature

t_s = Stabilization time

ρ = Fluid density

ρ_0 = Fluid density, at p = 0 psig and T = 59°F

α, β, γ = Coefficients.

REFERENCES

[1] Covan M and Sabins F. New Correlations Improve Temperature Predictions for Cementing and Squeezing. Oil and Gas Journal 1995; 21: 53-58.

[2] API RP 10B, Recommended Practice for Testing Well Cements. Washington, DC, 22nd Edition 1997.

[3] Kutasov IM. Method Corrects API Bottomhole Circulating-Temperature Correlation. Oil and Gas Journal 2002 July 15.

[4] García A, Ascencio F, Espinosa-Paredes G, Santoyo E, Gutiérrez H and Arellano VA. Numerical modeling of high-temperature deep wells in the Cerro Prieto geothermal field, México. Geofísica Internacional 1999; 38(4): 251-260.

[5] Kutasov IM. Applied Geothermics for Petroleum Engineers. Elsevier, Amsterdam, 1999: pp. 1-347.

[6] Kutasov IM and Sweetman M. Method Predicts Equivalent Mud Density for HPHT Wells. Oil and Gas Journal 2001; 24: 57-62.

[7] Eppelbaum LV, Kutasov IM and Pilchin AN. Applied Geothermics. Springer, Berlin – Heidelberg – London 2014; pp. 1-751. http://dx.doi.org/10.1007/978-3-642-34023-9_1

[8] Kutasov IM and Eppelbaum LV. Pressure and Temperature Well Testing. CRC Press (Taylor and Francis Inc) 2015; USA: pp. 1-276. http://dx.doi.org/10.1201/b19295-2

[9] García A, Hernández I, Espinosa-Paredes G and Santoyo E. TEMLOPI: A thermal simulator for estimation of drilling mud and formation temperatures during drilling of geothermal wells. Computers and Geosciences 1998; 24(5): 465-477. http://dx.doi.org/10.1016/S0098-3004(98)00025-9

[10] Espinosa-Paredes G, García A, Santoyo E and Hernández I. TEMLOPI/V.2: A computer program for estimation of fully transient temperatures in geothermal wells during circulation and shut-in. Computers and Geosciences 2001; 27(3): 327-344. http://dx.doi.org/10.1016/S0098-3004(00)00102-3

[11] Santoyo E, Santoyo S, García A, Espinosa Paredes G and Moya SL. Rheological property measurement of drilling fluids used in geothermal wells. Applied Thermal Engineering Jour 2001; 21(3): 283-302. http://dx.doi.org/10.1016/S1359-4311(00)00003-X

[12] Espinosa-Paredes G, Morales-Díaz A, Ulea-González U and Ambriz-García JJ. Application of a proportional-integral control for the estimation of static formation temperatures in oil wells. Marine and Petroleum Geology 2009; 26: 259-268. http://dx.doi.org/10.1016/j.marpetgeo.2007.11.002

[13] Kuliyev SM, Esman BI and Gabuzov GG. Temperature Regime of the Drilling Wells, Nedra, Moscow (in Russian) 1968.

[14] Kutasov IM, Caruthers RM, Targhi AK and Chaaban HM. Prediction of Downhole Circulating and Shut-in Temperatures. Geothermics 1988; 17(4): 607-618. http://dx.doi.org/10.1016/0375-6505(88)90046-6

[15] Kutasov IM. Empirical Correlation Determines Downhole Mud Density. Oil and Gas Journal 1988; 61-63.

[16] Wooley GR, Giussani AP, Galate JW and Wederlich HF. III Cementing Temperatures for Deep-Well Production Liners. SPE paper 13046, presented at the 59th Annual Techn Conf and Exhib. Houston, Texas 1984; 16-19. http://dx.doi.org/10.2118/13046-MS

[17] McMordie WC Jr, Bland RG and Hauser JM. Effect of Temperature and Pressure on the Density of Drilling Fluids. SPE Paper 11114, presented at the 57th Annual Techn Conf and Exhib of the SPE, New Orleans 1982; 26-29. http://dx.doi.org/10.2118/11114-MS

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