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Impact of Cuttings Concentration on ECD during Drilling

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Abstract

Mud hydraulics is considered one of the most important factors affecting drilling performance. One of the functions of drilling mud is to carry the cuttings out of hole. The cutting carrying process is dependent on many drilling conditions such as rate of penetration, mud rheology, flow rate, hole deviation, etc. Many hydraulics models have been developed by the industry over the past 2 decades. Almost all of these models calculate equivalent circulation densities (ECDs), which is very important to ensure the wellbore integrity and to avoid loss of mud and other non-productive time (NPT).

Normally, people predict ECD using the hydrostatic pressure and frictional pressure drop in annulus, without considering the cuttings concentration in the annulus. This could lead to under-estimated ECD values. To predict more correct ECD needs to consider cuttings concentration (volume fraction of cuttings) together with slip velocity of cuttings. As a matter of fact, all these variables are cross linked and coupled to each other.

This article addresses the correct way to calculate the cuttings concentration and improved prediction of ECD by considering the cuttings concentration in the annulus. Various case studies will show the impact of the cuttings concentration on ECD during drilling operations. Current study focuses on vertical wells.

Introduction

During drilling operations, it is important to maintain the pressure balance and keep the bottom hole pressure gradient between the pore pressure gradient and fracture pressure gradient to prevent influx of formation fluid into the wellbore or loss of circulation to the formation. For a given point A in annulus, with the measured depth, D ft and the corresponding true vertical depth, TVD ft, pressure at point A can be calculated as

$$P = P_{back} + P_h + \Delta P_a \tag{1}$$

P_{back}, the back pressure at surface, for open surface, usually is 14.5 psi. P_h, the hydrostatic pressure, is the static pressure of a column of fluid due to its weight. ΔP_a, the total frictional pressure drop in annulus from surface through depth D, is determined by the mud rheology and flow behavior. The rheology models most used in the drilling industry are Newtonian, Bingham Plastic, Power Law and Herschel-Bulkley. The most common flow behaviors are laminar, turbulent and transitional. Changing the mud velocity in annulus may change the flow behavior. Velocity depends on the condition of the mud pump and wellbore size and configuration.

ECD is defined as

$$ECD = \frac{P}{0.052TVD} \tag{2}$$

Without cuttings concentration (ECD1)

Normally, to predict ECD, without considering the cuttings concentration, the hydrostatic pressure is calculated as

$$P_h = 0.052TVD\rho_m \tag{3}$$

The ECD at point A is given by

$$ECD1 = \rho_m + \frac{P_{back} + \Delta P_a}{0.052TVD} \tag{4}$$

ECD1 is the apparent fluid density which results from adding annular friction to the density of annular mud. For a given pumping mud, usually, increasing flow rate will increase ΔP_a, therefore increase the ECD.

With cuttings concentration (ECD2)

During drilling operation, as the cuttings generated by the bit enter the annulus, the fluid will be the mixture of pumping mud and cuttings. The effective density of the mixture, ρ_e is defined by

$$\rho_e = \rho_m(1-f_s)+\rho_s f_s \tag{5}$$

So we have

$$P_h = 0.052TVD\rho_m + 0.052TVDf_s(\rho_s - \rho_m) \tag{6}$$

Although the cuttings concentration will affect the annulus frictional pressure drop ΔP_a , but the contribution is fairly small and usually can be ignored. So with equation (4) and (6), the ECD at point A is given by

$$\text{ECD2} = \text{ECD1} + f_s(\rho_s - \rho_m) \tag{7}$$

The ECD2 results from adding additional column weight to ECD1 due to the cuttings taking over partial of annular volume which was filled with the mud. ECD2 is directly affected by cuttings concentration and the density difference between cuttings and mud. For certain pumping mud, if the cuttings concentration is high, its contribution to ECD is high and can't be ignored. It is very important to predict the cuttings concentration to obtain an actual ECD and avoid the loss of circulation, formation and borehole wall damage.

Calculation of cuttings concentration

The cuttings concentration is the volume fraction of cuttings in the annulus fluid, and is defined by

$$f_s = \frac{q_s}{q_s + F_T \times q_m} \tag{8}$$

Where

$$q_s = A_b \times ROP \times (1-\phi) \tag{9}$$

F_T , the cuttings transport ration is defined as below.

$$F_T = 1 - \frac{V_{sl}}{V_a} \tag{10}$$

Where

$$V_a = \frac{q_m}{A_a(1-f_s)} \tag{11}$$

Because of the extreme complexity of the flow behavior, the cuttings slip velocity, V_{sl} is obtained only for the very idealized conditions. It is depended primarily on empirical correlations such as the correlations of Mores, Chien, and Walker and Mayes. The following correlation is based on Chien correlation, and only used for vertical well and lower particle Reynolds number.

$$V_{sl} = \frac{0.0075\mu_a}{\rho_f d_s}\left[\sqrt{\frac{36800d_s}{(\frac{\mu_a}{\rho_f d_s})^2}(\frac{\rho_s-\rho_f}{\rho_f})+1}-1\right] \tag{12}$$

Where μ_a , the apparent viscosity, is given by

$$\mu_a = 100k \times (\frac{144V_a}{D_2 - D_1})^{(n-1)} \times (\frac{2n+1}{n})^n \tag{13}$$

If q_{sl} , the cuttings slip rate, is defined as below

$$q_{sl} = A_a V_{sl} \tag{14}$$

Then from equation (10), (11) and (14), we have

$$F_T = 1 - \frac{q_{sl}(1-f_s)}{q_m} \tag{15}$$

Combine the equation (8) and (15), we have

$$q_{sl} \times f_s^{\ 2} + (q_s + q_m - q_{sl}) \times f_s - q_s = 0 \tag{16}$$

Solving equation (16), we have

$$f_s = \frac{-b+\sqrt{b^2-4ac}}{2a} \tag{17}$$

Where

$a = q_{sl}$

$b = q_s + q_m - q_{sl}$

$c = -q_s$

Since q_{sl} and f_s are cross linked, a numerical method (trial and error method) is used to obtain the value of f_s .

Step 1: assuming a cuttings concentration f_{s1} , using equation (11) to calculate the V_a .

Step 2: using equation (13) to calculate μ_a .

Step 3: using equation (12) to calculate V_{sl}.

Step 4: using equation (9) and (14) to calculate q_s and q_{sl}.

Step 5: using equation (17) to calculate f_{s2}.

Step 6: comparing f_{s1} with f_{s2}. If f_{s1} and f_{s2} is within the error tolerance, then f_{s1} is the current cuttings concentration in annulus. If not, then repeat step 1 through 6, until the cuttings concentration is found.

Case study

Total depth:	10,000 ft
Casing:	8.755 in. ID, set at 6,500 ft
Open hole:	8 ½ in. from 6,500 ft to 10,000 ft
Drill pipe:	9,500 ft of 4 ½ in. OD and 3.826 in. ID
Drill collar:	500 ft of 6 ¾ in. OD and 2 ¼ in. ID
Surface equipment:	type 3
Mud weight:	10.5 ppg
PV:	19.5 cp
YP:	8 lbf /100sq ft
Cuttings diameter:	0.25 in
Cuttings density:	21 ppg
ROP:	20 ft/hr

Table 1. Cuttings concentration profile at variable flow rates

Flow rate (gpm)	Cuttings concentration (%)		
	Interval 1	Interval 2	Interval 3
78	10.74	8.03	2.44
94	4.89	3.96	1.76
120	2.28	2.02	1.21
286	0.48	0.47	0.40
400	0.31	0.30	0.27
800	0.14	0.14	0.13

Interval 1: 0 – 6,500 ft; Interval 2: 6,500 – 9,500 ft; Interval 3: 9,500 – 10,000 ft

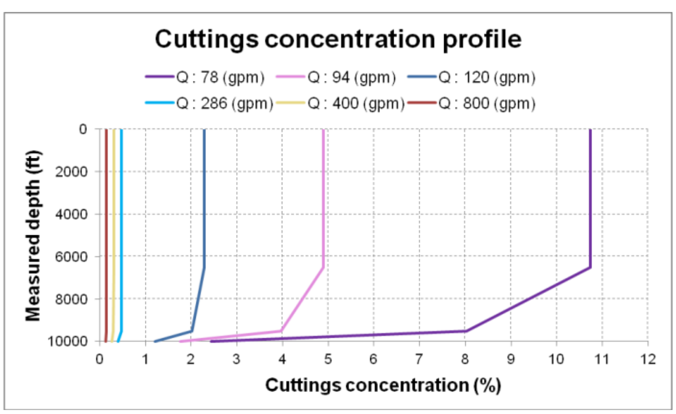

Fig. 1: Cuttings concentration profile at variable flow rates

With ROP at 20 ft/hr, when flow rate increases from 78 gpm to 800 gpm, cuttings concentration in interval 1 decreases from 10.74% to 0.14%. Pumping at 78 gpm, interval 1 with the least cross section area has the highest cuttings concentration, 10.74%. Nevertheless interval 3 with the biggest cross section area has the lowest cuttings concentration, 2.44%. Cuttings transport is influenced by the annular velocity profile. Increasing flow rate or decreasing the annulus cross section area will increase the annular velocity. Very high annular velocity may not be possible because of hydraulic and physical limitations, but increasing annular velocity will always decrease the cuttings concentration.

With ROP at 20 ft/hr, flow rate, 94 gpm can be defined as the required flow rate to clean the hole. Pumping above 94 gpm, the cuttings concentration stays below 5%, the maximum acceptable value for the hole cleaning by the drilling engineer.

Table 2. ECD at bottom with/without cuttings

Flow rate (gpm)	ECD at bottom (ppg)	
	ROP: 0 (ft/hr)	ROP: 20 (ft/hr)
78	10.72	11.72
94	10.72	11.19
120	10.73	10.95
286	10.78	10.82
400	10.84	10.87
800	11.42	11.44

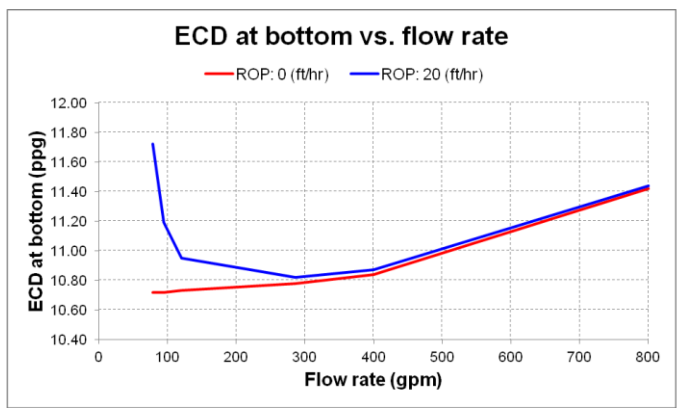

Fig. 2: ECD at bottom with/without cuttings

Without considering cuttings concentration (red line, ROP = 0 ft/hr), Increasing the flow rate will increase the frictional pressure drop. Thus the higher the flow rate, the higher the ECD.

With considering cuttings concentration (blue line, ROP = 20 ft/hr), when the flow rate increases,

- Before the flow rate reaches 286 gpm, even though the frictional pressure drop in annulus increases, but the average density of fluid in annulus decreases due to the decrease of the cuttings concentration. This results the decrease of ECD at bottom;

➢ After the flow rate reaches 286 gpm, table 1 shows that the cuttings concentration is as low as 0.4%, its contribution to ECD is limited and frictional pressure drop is dominant. This results the increase of ECD at bottom.

Table 3. ECD at bottom vs. flow rate at variable ROPs

Flow rate (gpm)	ECD at bottom (ppg)					
	ROP: 0 (ft/hr)	ROP: 20 (ft/hr)	ROP: 50 (ft/hr)	ROP: 80 (ft/hr)	ROP: 100 (ft/hr)	ROP: 150 (ft/hr)
78	10.72	11.72	12.31	12.72	12.94	13.39
94	10.72	11.19	11.67	12.04	12.25	12.69
123	10.73	10.94	11.22	11.47	11.62	11.97
152	10.73	10.87	11.06	11.24	11.35	11.61
171	10.74	10.85	11.00	11.15	11.25	11.47
218	10.75	10.82	10.93	11.03	11.10	11.26
265	10.77	10.82	10.90	10.98	11.03	11.16
286	10.78	10.82	10.90	10.97	11.02	11.13
310	10.79	10.83	10.90	10.96	11.00	11.11
360	10.84	10.87	10.91	10.96	10.99	11.07
390	10.84	10.87	10.91	10.97	10.99	11.07
460	10.87	10.90	10.94	10.98	11.01	11.07
500	10.91	10.93	10.97	11.01	11.03	11.09
800	11.42	11.44	11.46	11.48	11.50	11.53

■ In red background: At specified ROP, the corresponding flow rate can be defined as the required flow rate to clean the hole to maintain the cuttings concentration below 5%.

■ In blue background: ECD starts to increase as flow rate increases.

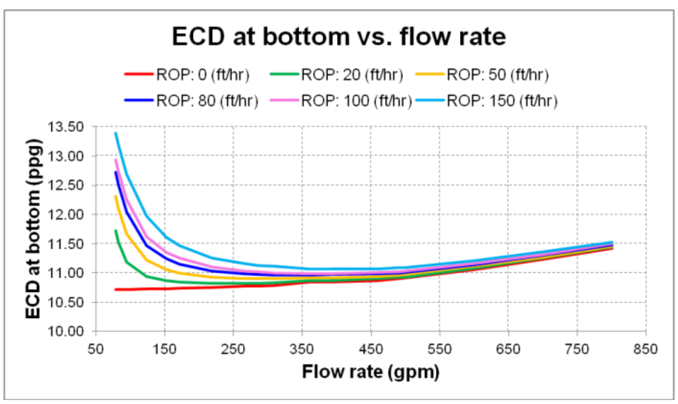

Fig. 3: ECD at bottom vs. flow rate at variable ROPs

At the same flow rate, the higher the drilling rate, the higher the ECD at bottom. With insufficient hole cleaning condition, cuttings settling down will result a high cuttings concentration which must be considered when predicting the ECD in design stage. In turn, during drilling operation, the increasing ECD can indicate the cuttings accumulation and insufficient hole cleaning.

Conclusion

On the basis of the cases studied, cuttings concentration will affect the pressure and ECD in annulus. At design stage, cuttings concentration should be calculated to predict the actual ECD at bottom to prevent the loss of circulation, differential sticking and other hazard damage of the wellbore.

Increasing flow rate or decreasing annulus cross section area will always increase hole cleaning.

Cuttings density and mud density directly affects the ECD when considering cuttings concentration. Equation (7) shows that for sufficient hole cleaning conditions, ECD change can vary from 0 to 0.6 ppg (f_s = 5%, ρ_s = 21 ppg and ρ_m = 9 ppg). For insufficient hole cleaning conditions, it can vary more. Actual ECD prediction is more important for those wells with a narrow margin between the pore and fracture pressure gradient.

The other parameters that are not discussed in this paper but affect the transportation of cuttings are mud viscosity, cuttings density, cuttings size and pipe rotational speed.

The procedures to calculate cuttings concentration in this paper is only valid for vertical wells. For inclined well, it is more difficult to transport the cuttings to the surface, hole cleaning is more complicate and important. Further study on inclined wells is recommended.

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Nomenclature

P = *Pressure at point A, (psi)*

ECD = *Equivalent circulation density, (ppg)*

ROP = *Bit penetration rate, (ft/hr)*

ρ_m = *Density of the pumping fluid, (ppg)*

ρ_s = *Cuttings density, (ppg)*

ρ_e = *Effective annulus mud density, (ppg)*

f_s = *Cuttings concentration, (%)*

μ_a = *Apparent viscosity, (cp)*

A_a = *Area of annulus, (in^2)*

A_b = *Area cut by the bit, (in^2)*

V_a = *Fluid velocity, (ft/s)*

V_T = *Cuttings transport velocity, (ft/s)*

q_s = *Feed rate of cuttings, (gpm)*

q_m = *Fluid flow rate, (gpm)*

q_{sl} = *Cuttings slip rate, (gpm)*

ϕ = Rock porosity, (-)

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