RESEARCH ARTICLE

Transportation of Cuttings in Inclined Wells

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ABSTRACT

One of the most important functions performed by drilling fluid is the removal of cutting from the bottom of the hole to the surface. This function must be performed efficiently if not, the cuttings produced during drilling process will accumulate in the annulus. This problem in directional drilling is featured by gravitational forces. Problems resulting from inefficient cutting transport include pipe stuck, wear of bit, reduction in penetration rate, high torque, and drag with many other problems encountered. In high-angle deviated wells, the cutting goes through a complex path to the surface where some of the cuttings gravitate to the low side of the well. Reduction in any problem associated with improper cutting transport requires good understanding in cutting transport mechanisms. This research focuses on calculating the minimum annular velocity of drilling fluid and minimum pump flow rate which is required to achieve hole cleaning and lifting of the cutting to the surface, taking into consideration, the main parameters that affect the coring capacity of the drilling fluid, for this purpose, data of a deviated well (X) located in Iraq are collected to determine slip velocity, annular velocity, critical flow rate, and carrying capacity index taking in consideration the mud used and the angle of the deviation using the drilling formula spreadsheet V1.6.

Keywords: Annular Velocity, Cuttings Transportation, Directional Drilling, Hole Inclination, Inclined Wells

1. INTRODUCTION

The process of cutting transportation and proper hole cleaning is substantial in any drilling program. The success of any drilling operation is the result of efficient and proper cleaned hole. Hole cleaning is the capability of the drilling fluid to transport the cutting produced during drilling operations up to the surface and suspend the cuttings (Bourgoyne and Millhein, 1991). Many studies on hole cleaning have been carried out by different scientists and researchers over the past decades. The numbers of highly deviated and horizontal wells have increased significantly as a result of improved related knowledge and technology. Integration of optimum drilling fluid properties and implementation of best drilling practices are necessary for good hole cleaning. As a result, hydraulic simulation or experimental work of wellbore cleaning in drilling operation is highly recommended before drilling. For adequate hole cleaning, drilling fluid is expected to possess such rheological properties that can efficiently transport cuttings to surface (Akram and Maha, 2017). Cutting carrying index (CCI) which is a function of drilling fluid is used as simple tool to determine the efficiency of hole cleaning in drilling operations (Duan et al., 2010). Different mechanisms which control wellbore angles within different ranges define (a) wellbore configuration (depth, hole angle, hole size, or casing/wellbore inside diameter, and pipe size), (b) fluid properties (density and rheological properties), (c) cuttings characteristics (density, size, shape, bed porosity, and angle of repose), (d) pipe eccentricity and rotary speed, and (e) cuttings bed heights and annular cuttings concentrations as function of operating parameters (flow rate and penetration rate) (Duan et al., 2010). The efficiency in vertical and deviated wellbores has been reported to depend on some factors such as average fluid velocity, hole geometry and inclination, the size of cuttings and their shape, concentration of the cuttings, cuttings transport velocity, fluid flow regimes, drill pipe rotation, pipe

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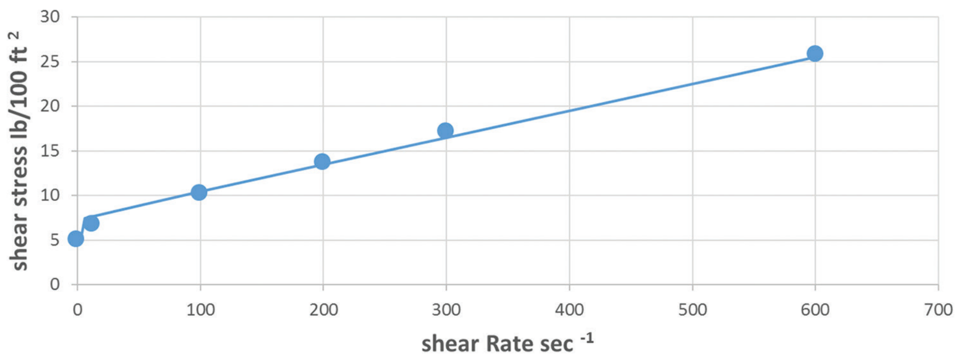

Figure 1. Shear rate and shear stress relationship

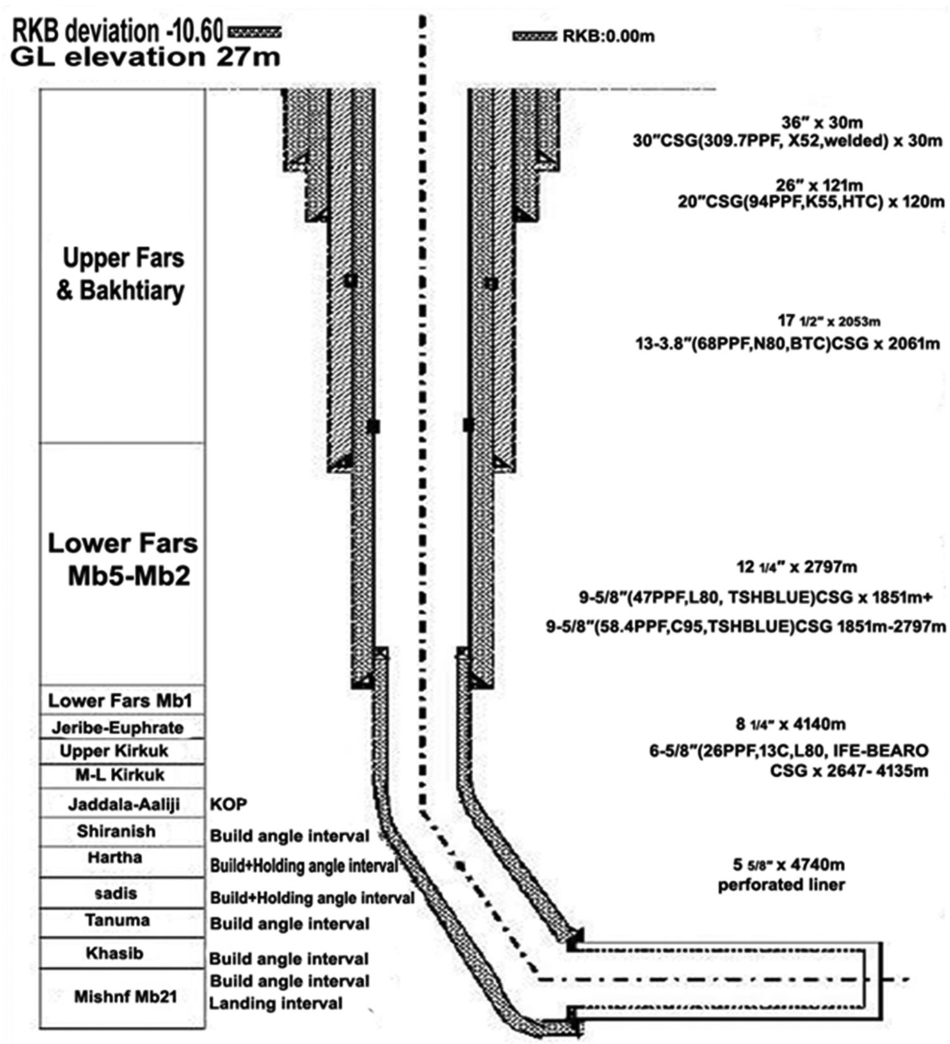

Figure 2. Schematic of the horizontal well

eccentricity, fluid properties and rheology, rate of penetration, and multiphase flow effect. Any change in the angle of deviation of a well results in changing the lifting capacity of a drilling mud. As the angle of the inclination of well increases, the ability of drilling mud to lift the drill cuttings (Bourgoyne and Millhein, 1991). This happens due to the accumulation of the cuttings on lower side of the annulus and forming moving or stationary cutting beds instead of being carried out of the annulus. Therefore, the drilling mud requires more power to remove the cuttings in bended area of the well.

2. CALCULATION METHODS

The drilling formula sheet V16 is used for calculating most of the important factors. This sheet contains all the formulas needed for calculating the hydraulics, well control, and equipment data. This Drilling Formula Sheet is based on the book Applied Drilling Circulation Systems book by Ciuo and Liu (2011).

According to the mentioned sheet and book, the calculations are done in the following manner:

- For calculating critical flow rate according to the sheet, the following equations are used.

The effective viscosity equation for critical velocity is listed below:

$$\mu_{ea} = 100k_a\left[\frac{144v_a}{D_h - D_o}\right]^{n_a-1} \quad (1)$$

Table 1. Drilling fluid prosperities

Rpm	3	6	100	200	300	600
Reading φ	5.5	6.5	9.5	12.5	15.5	2.4

Table 2. Shear rate and shear stress values

rpm	Y (sec^{-1})	Φ reading	τmeas (lb/100 ft^2)
3	5.4	5.5	5.5
6	10.4	6.5	7.5
100	175	9.5	10.5
200	345	12.5	13.5
300	520	15.5	16.5
600	1030	24	25.5

The Reynolds number equation for critical velocity is listed below:

$$\mathrm{Re}_a = \frac{928v_a(D_h - D_0)w}{\mu_{ea}\left(\frac{2n_a+1}{3n_a}\right)^{n_a}} \quad (2)$$

The critical annular velocity equation is listed below:

$$v_c = \left[\frac{(3470 - 1370n_a(100)K_a(\frac{2n_a+1}{3n_a})^{n_a}}{928W(D_h - D_o)(\frac{144}{D_h - D_o})^{1-n_a}}\right] \quad (3)$$

After we get the critical velocity, we can figure out the critical flow rate by the following equation:

$$Q_c = (2.45)V_c\left(D_h^2 - D_0^2\right) \quad (4)$$

- For calculating optimum flow rate according to the sheet,

The equation is finding the optimum flow rate based on maximum hydraulic horsepower or maximum impact force using the following equations:

$$0.35P_S = 0.0001[C_{se}+L_p(C_{pa}+C_{pb})+L_c(C_{ca}+C_{cb})]WV_f Q^{1.86} \quad (5)$$

Solve for Q:

$$Q = \sqrt[1.86]{\frac{0.35p_s}{0.0001\left[C_{se}+L_p\left(C_{pa}+C_{pb}\right)+L_c\left(C_{ca}+C_{cb}\right)\right]WV_f}} \quad (6)$$

Optimum flow rate at maximum impact force:

$$0.52P_s = 0.0001[C_{se}+L_p(C_{pa}+C_{pb})+L_c(C_{ca}+C_{cb})]WV_f Q^{1.86} \quad (7)$$

Solve for Q:

$$Q = \sqrt[1.86]{\frac{0.52p_s}{0.0001\left[C_{se}+L_p\left(C_{pa}+C_{pb}\right)+L_c\left(C_{ca}+C_{cb}\right)\right]WV_f}} \quad (8)$$

Table 3. Functions which are required to perform AAPE calculation

τmeas (lb/100ft^2) τ=1.067*ϕ	τcal (lb/100ft^2) τ=KYn	$\left\lvert\frac{\tau\ mmean - \tau\ cal}{\tau\ meas}\right\rvert$ Power-law model	τcal (lb/100ft^2) τ=τy+μp Y	$\left\lvert\frac{\tau\ mmean - \tau\ cal}{\tau\ meas}\right\rvert$ Bingham plastic model
5.34	4.50	0.25	6.70	0.25
6.4	5.15	0.19	6.70	0.04
9.6	9.60	0.09	9.00	0.06
11.70	12.70	0.04	12.00	0.05
14.90	15.60	0.02	16.00	0.02
23.40	25.00	0.01	25.00	0.01

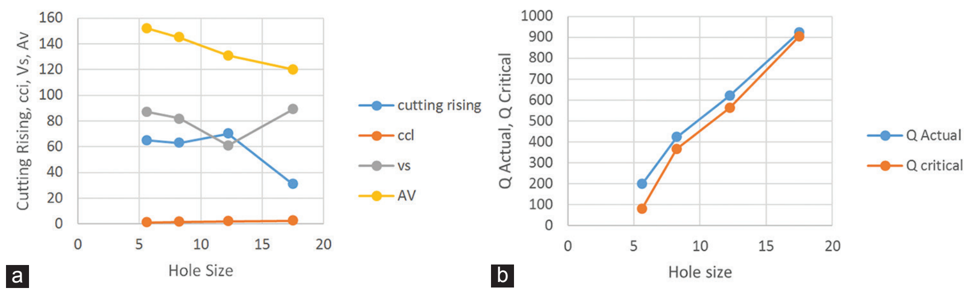

Figure 3. (a and b) Final results of cutting rising velocity and flow rates with hole size

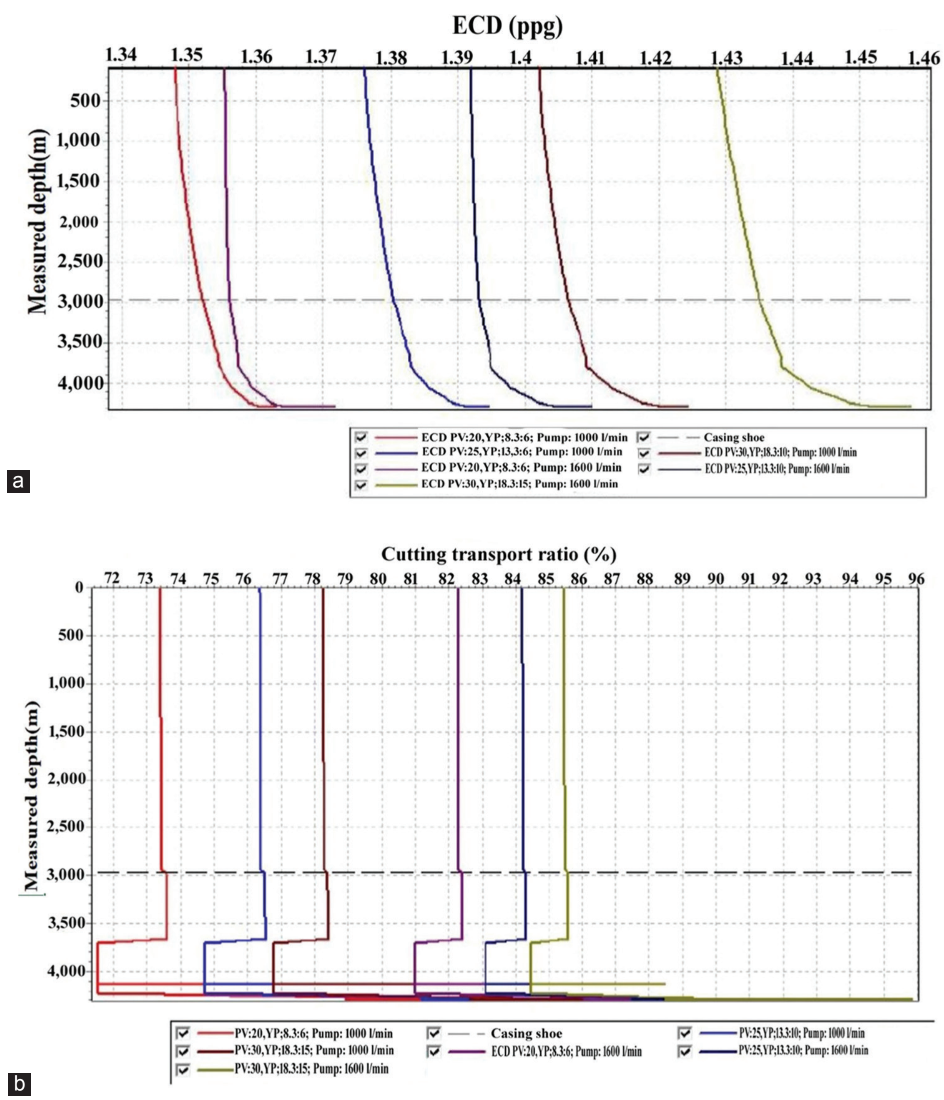

Figure 4. (a) ECD measured depth relationship, (b) cutting transport ratio and measured depth relationship for MW=1.36 gm/cm^3

Vf can be determined by this equation: $Vf=(PV\div W)^{0.14}$ (9)

For calculating slip velocity according to the sheet, the following equations are used:

Determine annular velocity with the following equation:

$$AV = \frac{24.5\times Q}{Dh^2 - Dp^2} \quad (10)$$

Table 4. Predicted stratigraphy and lithology description (field data)

Strata			Top Depth (m TVD)	Lithology description
Tertiary	Upper Fars			Upper mainly clay. Lower mainly shale interbed sand
	Lower Fars	mb5	1972.5	Alternation of anhydrite. Shale and dolomite
		mb4	2289.5	Alternation of anhydrite. Shale and salt
		mb3	2625.5	Thick bed of Anhydrite. Interbedded with salt and shale with rare limestone
		mb2	2762.5	Massive salt
		mb1	2796.5	Anhydrite with thin interaction of shale and shaly dolomite
	Jeribe- Euphrate		2837.5	massive dolomite, locally limestone anhydritic interbed reddish brown shale
	Upper Kirkuk		2882.5	mainly dolomite interbeds of sandstone, limestone and mudstone
	BU		3022.5	sandstone
	Middle- Low Kirkuk		3059.5	shale and limestone
	Jaddala		3202.5	Argillaceous limestone, Marl, Shale and chert
	Aaliji		3347.5	Limestone
Cretaceous	Shiranish		3392.5	Argillaceous limestone
	Hatha		3439.5	chalky and argillaceous Limestone
	Sadi		3479.5	Argillaceous Limestone and Marl with shale
	Tunuma		3634.5	shale, Limestone with marl
	Khasib		3654.5	Compact limestone
	Mishrif	MA1	3706.5	Compact limestone
		MA2	3729.5	Mainly Grainstone
		MA3	3744.5	Mainly limestone
		MA11	3779.5	Compact limestone interbed thin packstone
		MA12	3834.5	Compact limestone interbed thin packstone
		MA21	3842.5	mainly Grainstone
TD				

Table 5. Well trajectory data

Well name	XXX	
First KOP (m)	3320	
Buildup rate (°/30m)	3.50	
Holding inclination (°)	19.27	
Azimuth (°)	299.05	
Second KOP (m)	3558.64	
Buildup rate (°/30m)	4.00	
Holding inclination (°)	89.93	
Azimuth (°)	299.05	
Target data		
X (m)	710638	710114
Y (m)	3569594	3569885
Z (m)	3842.90	3843.60
Max inclination	89.93	
TD (m)	4740.17	
TDV (m)	3843.60	
Displacement (m)	1108.33	

Determine cutting slip velocity with the following equation:

$$V_s = 0.45\left(\frac{PV}{MW \times Dp}\right)\left[\sqrt{\frac{36,800 \times Dp}{\left(\frac{PV}{MW \times Dp}\right)^2} \times \left(\frac{DenP}{MW} - 1\right) + 1} - 1\right] \quad (11)$$

The CCI according to the formula sheet used is calculated by the following method:

$$CCI = \frac{K(AV)(MW)}{400,00} \quad (12)$$

$$n = 3.322 \log \frac{(2PV + YP)}{(PV + YP)} \quad (13)$$

$$K = (511)^{1-n}\,(PV + YP) \quad (14)$$

- For calculating the average absolute percentage error, the following equation is used:

$$AAPE[\frac{1}{N}\sum_{i=1}\left|\frac{(z\ meas - z\ calc)i}{(z\ meas)i}\right|] \times 100 \quad (15)$$

3. DATA AND RESULTS

The Fann-VG readings are converted to shear stress (Ib/100 ft^2) and the rpm values to shear rate in sec^{-1} using the relations (Rabia, 1998). Table 1 presents the dial readings at different RPM of the Fann-VG meter.

$\tau meas = 1.067\ \phi$

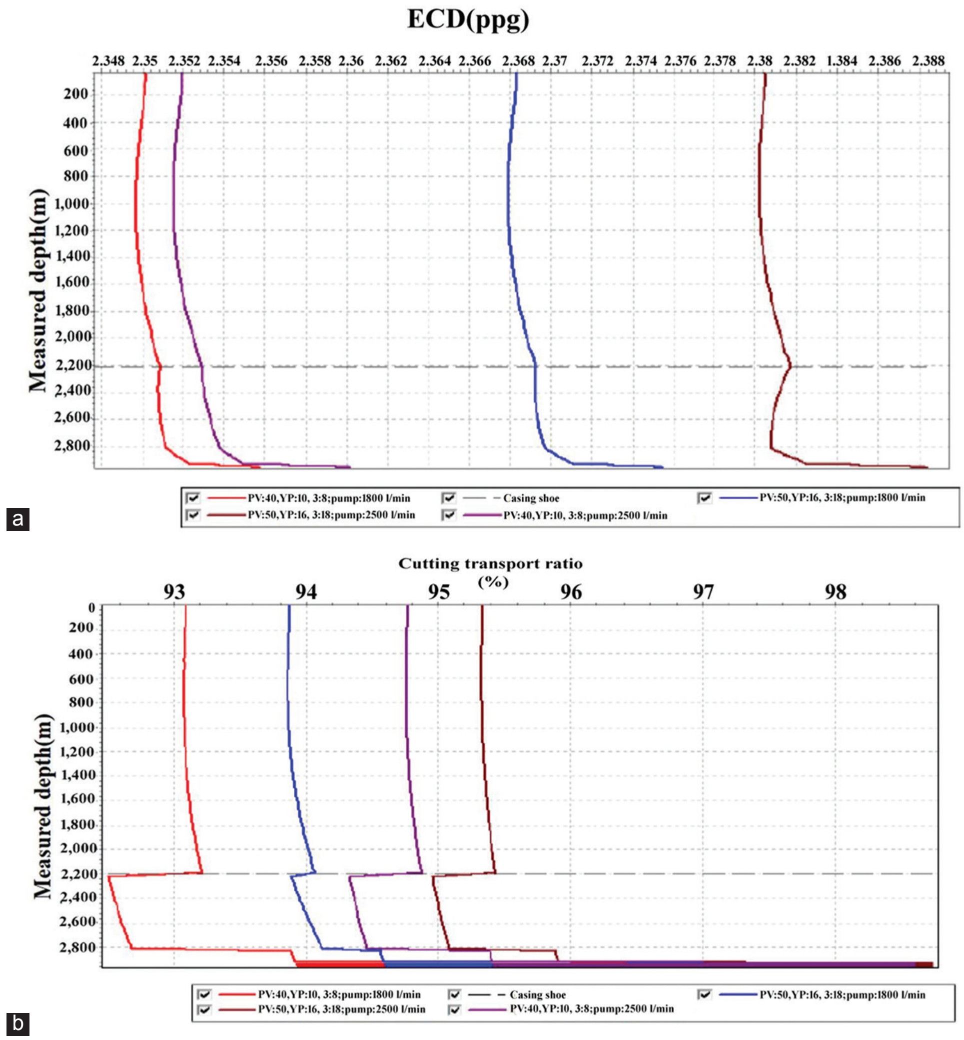

Figure 5. (a) ECD measured depth relationship, (b) cutting transport ratio and measured depth relationship for MW=2.32 gm/cm^3

Table 6. Programmed fluid type and properties by intervals

Hole size (in)	36″	26″	17–1/2″	12–1/4″	8–1/4″	5–5/8″
Hole intervals (m)	0–30	30–121	121–2053	2053–2797.5	2797.5–4140	4140–4740
Fluid type	Bent gel mud	Bent gel mud	KCL polymer	HIBDRIL	Undersaturated salt polymer system	Solid-free reservoir drill-in fluid
Density (g/cm^3)	1.05	1.05	1.05–1.30	2.20–2.30	1.15–1.38	1.21–1.28
PV (mPa.s)			ALAP	ALAP	ALAP	ALAP
YP (Pa)			6–15	5–16	8–14	5–10
GEL 10″/10′ (Pa)			2–8/3–10	3–8/5–12	3–5/5–8	2–4/3–6
API FL (mL)			8–20	3–8	2–5	2–5
pH			9–10	9–10	10.5–11.5	9–10

All the calculations are done for cutting size=0.5 in and cutting density = 21.7 ppg

$\gamma = 1.703 * rpm.$

$\tau_{calc} = K(\gamma)^2$

The results are shown in Table 2. Figure 1 is used to define which model our fluid obeys to choose the proper equations.

Values of n are calculated using equation 13 and values of K are calculated using equation 14.

Table 3 shows that the best non-Newtonian rheological model which fits the rheogram of the drilling fluid using

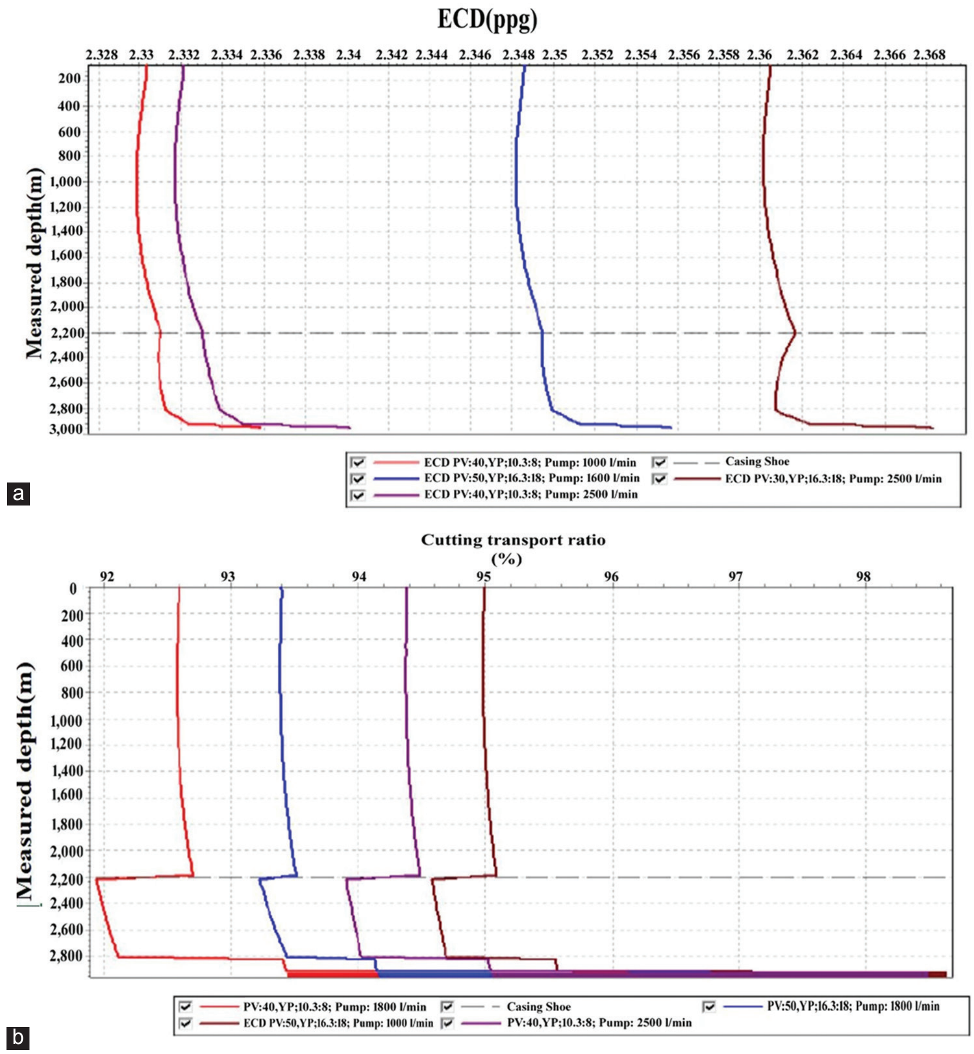

Figure 6. (a) ECD measured depth relationship, (b) cutting transport ratio and measured depth relationship for MW=2.30 gm/cm³

Table 7. Final results

Depth (m)	Hole size	MW g/cc	Min. AV (ft/m)	Q critical (gal/min)	Q actual (gal/min)	Vs (ft/min)	Cutting rising velocity (ft/min)	Pv	yp (pa)	ccl
2053	$17\frac{1}{2}$	1.15	120	904	925	89	31 - good	ALAP	11	2.5 good
2797.5	$12\frac{1}{4}$	2.25	131	563	621	61	70 - good	ALAP	12	2.1 good
4140	$8\frac{1}{4}$	1.26	145	365	423	82	63 - good	ALAP	10	1.6 good
4740	$5\frac{5}{8}$	1.24	152	79	198	87	65 - good	ALAP	7	1.02 good

AV: Annular velocity, ft/min

equation (15) is 7.1% (Aswad, 1996) and is the power-law model with AAPE 6–8% while for Bingham plastic model.

Table 4 shows the predicted stratigraphy and lithology description (field data). While Table 5 presents the well trajectory data which are shown in Figure 2.

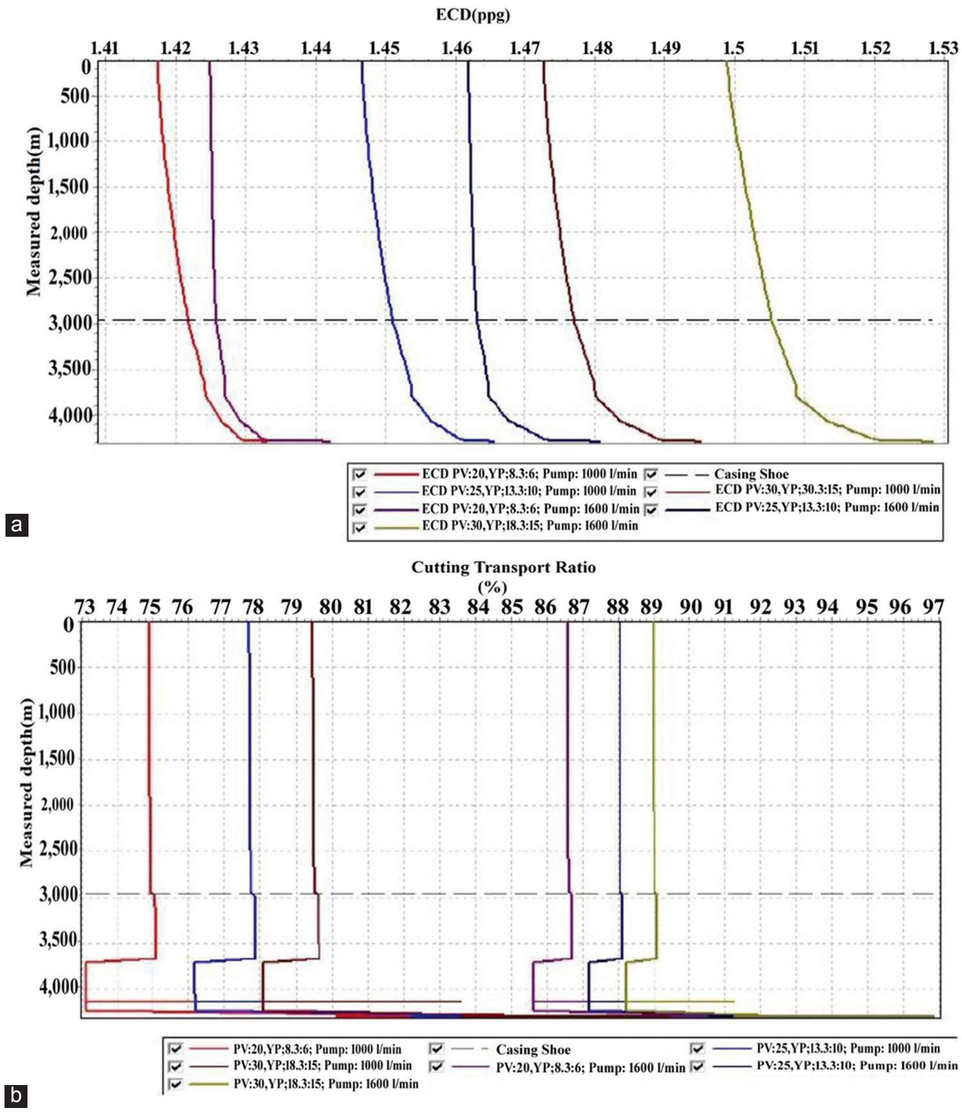

Figure 7. (a) ECD measured depth relationship, (b) cutting transport ratio and measured depth relationship for MW=1.35 gm/cm^3

4. ANALYSIS AND DISCUSSION OF THE RESULTS

Table 6 shows the programmed fluid type and properties by intervals. Final results are presented in Table 7 along with Figure 3. From the results, the carrying is >0.5 for the chosen interval which means that cutting was transported to the surface efficiently. Furthermore, by calculating the annular velocity and slip velocity, the net cutting rise velocity was determined to give good of bit cutting movement to surface. Caring capacity is affected by mud weight and the result is the noticeable change in other parameters such as Yp of the fluid. High mud weight is necessary for controlling Yp, for example, in $12\frac{1}{4}$ inches. Interval Yp was maintained at high level to reduce cuttings bed and bridge.

The hole size has effect on flow rate as well when the hole size increases higher flow rate is needed for cleaning the well and that means more pumping is needed to reach the minimum annular velocity needed for hole cleaning. The mud tends to move faster in small hole size rather than in large holes from carrying capacity of cuttings and hole cleaning point of view. Hole cleaning is also affected by density of the cuttings. The increase in the cutting density leads to increasing the mud weight in the annulus, which in turn results in increasing the slip velocity of the cuttings. Any increase in slip velocity means that higher flow rate is required to accelerate the mud in the annulus for a better hole cleaning. For this reason, it is important to take the cuttings density in consideration.

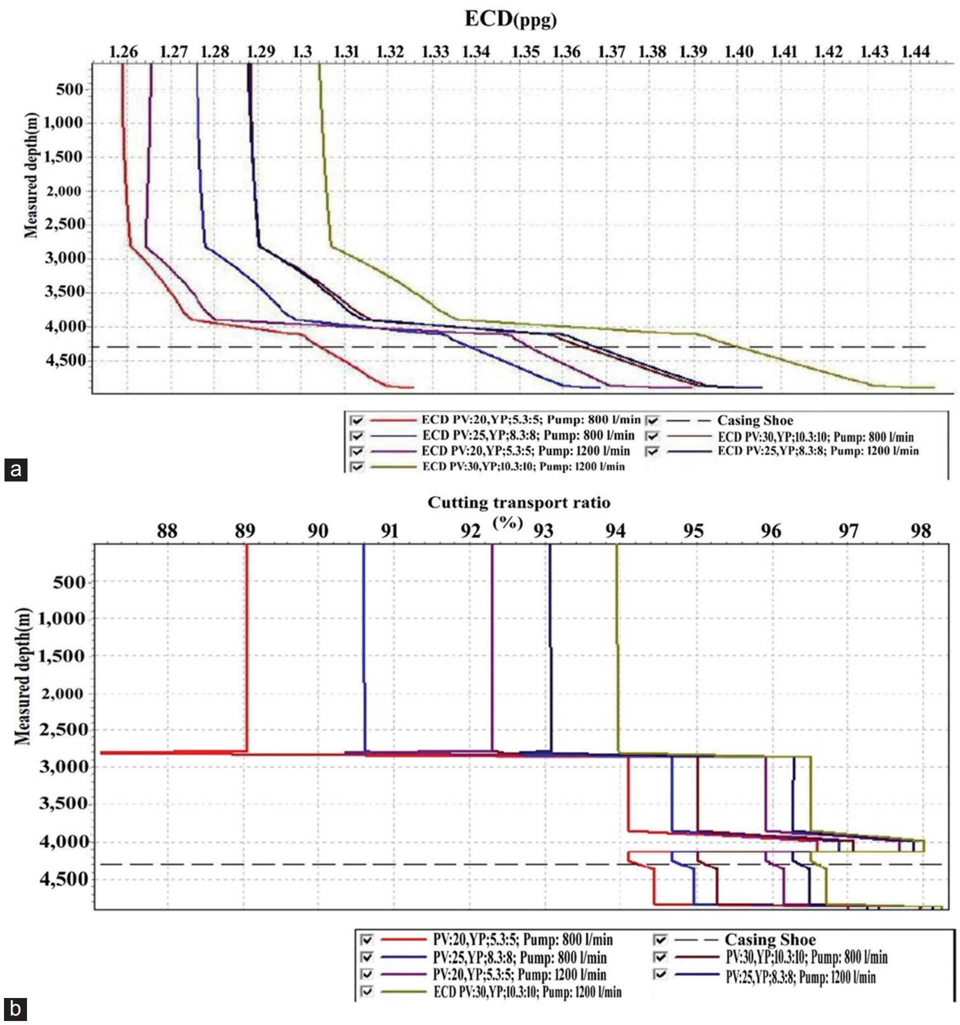

Figure 8. (a) ECD measured depth relationship, (b) cutting transport ratio and measured depth relationship for MW=1.21 gm/cm^3

Rate of penetration is also offering the cutting transporting that is by controlling the cuttings density in the wellbore. When there is low ROP that means the mud has more time to transport the cuttings due to the smaller slip velocity of cuttings, but it should be taken in consideration, lower ROP means the cost of drilling will increase due to larger time the operation will take.

The hole inclination is affecting the flow rate when the inclination of the hole increases that mean higher flow rates are needed. The need of higher flow rate will be too obvious when the well reduces 50º angle which means high pump efficiency is needed for this reason, but with cleaning the mud properties, it will be more capable to control the flow rate in specific range. Figures 4-9 show the relation of ECD and cutting transport ratio with measured depth for ROP = 10 m/h and different specific gravities of mud. Results of the graphs show that when MW = 2.30 g/cm^3, different properties and flow rates, both ECD and cuttings transport ratio can meet the fluid demand and when MW 2.32 g/cm^3, condition the properties as low as possible, recommend suitable flow rate for engineering. W equal MW and equal flow rate, viscous and get strength affect ECD more, with the same properties of the drilling mud, flow rate affects ECD more.

5. CONCLUSIONS

1. It was found that when MW = 2.30 g/cm^3, different properties and flow rates, both ECD and cuttings transport ratio can meet the fluid demand and when MW

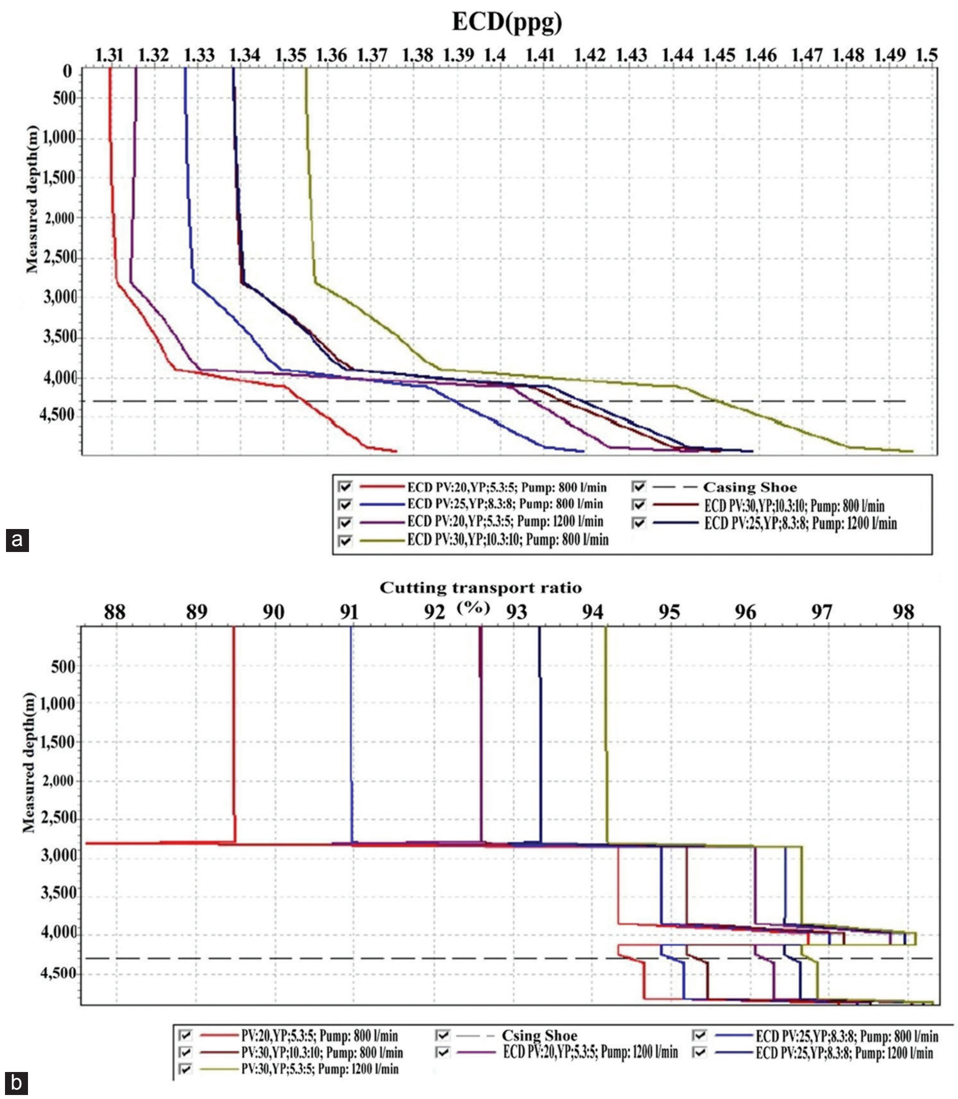

Figure 9. (a) ECD measured depth relationship, (b) cutting transport ratio and measured depth relationship for MW=1.26 gm/cm³

2.32 g/cm³, condition the properties as low as possible, recommend suitable flow rate for engineering.

2. With equal MW and equal flow rate, viscous and get strength affect ECD more, but with the same properties of the drilling mud, flow rate affects ECD more.
3. The flow velocity of the mud depends on the hole size; mudflow faster in small hole size than the case of larger hole size, this is valid for the carrying of cuttings and hole cleaning point of view.
4. Density of cuttings is a major factor that affects the hole cleaning efficiency, if there is an increase in density of cuttings; this leads to increase of mud weight in the annulus and eventually leads to increase in slip velocity of the cuttings.
5. It is essential to consider the cuttings density; this is for the purpose of mud acceleration on the annulus for good hole cleaning. The good hole cleaning requires high flow rate which occurs when slip velocity increases.
6. At low ROP, longer time needed for the cuttings to be transported due to lower slip velocity of the cuttings. Low ROP means higher drilling cost due to longer operational time.
7. Hole inclination is a major factor, increase in inclination requires a high flow rate, this becomes more obvious when the well reaches 50° and this will require a higher efficiency pump. In high inclined section, the flow should be turbulent to transfer the cuttings to the surface.
8. As the velocity of the cutting being raised increase, the carrying capacity index and hence the hole cleaning efficiency increase.

9. There is a direct proportional relationship between the slip velocity and the cutting density. Increasing the cutting density will lead to increase in slip velocity of the cuttings falling through the annulus down. However, while the cuttings diameter increases, slip velocity decreases, and hence, the annulus velocity should increase to clean the hole size to a higher extent.

6. RECOMMENDATIONS

It is recommended to do the following:

1. A study work on the cleaning efficiency on horizontal wells
2. Research study on the effect of hole cleaning during the underbalanced drilling
3. Study the role of hole cleaning in high pressure/high temperature of high inclined wells.

7. NOMENCLATURE

- AV - Annular velocity, ft/min.
- CCa - Coefficient for the annulus of drilling collars.
- COB - Coefficient through inside of drill collars.
- CSe - Surface coefficient.
- Cpa - Coefficient for the annulus of pipe.
- Cpb - Coefficient through inside of pipe and tool joint
- Denp - Cutting density, ppg.
- Dh - Diameter of wellbore, in.
- Do - Outside diameter of tubular, in.
- Dp - Diameter of drill pipe, in.
- ECD - Equivalent circulating density, Ib/gal.
- K - Power-law constant (power law)
- Lc - Drill collar length, ft.
- Lp - Drill pipe length, ft
- n- Flow behavior index (power law)
- Ps - Surface pressure, ft.
- Pv - Plastic viscosity, cp
- Q - Flow rate, gpm.
- Rea - Reynolds number in annulus.
- Vc - Critical velocity ft/sec
- Vf - Viscosity correction factor.
- Vs - Slip velocity, ft/sec
- W - Mud weight, ppg
- τ - Shear stress, Ib/100ft^2
- γ - Shear rate, sec^{-1}.

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