Rheological Effects of Power Law Drilling Fluids on Cuttings Transportation in Non-Vertical Wellbores*

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Abstract

Cuttings transportation in non-vertical boreholes is necessary for oil and gas wells. Efficient cuttings removal from a wellbore during drilling is critical for cost-effective drilling as high annular cuttings buildup often leads to high risk of stuck pipe, reduced rate of penetration and other impediments to standard drilling and completion procedures. This study investigates rheological parameters influence on the removal of cuttings in non-vertical boreholes in the course of drilling. In this study, twelve mud samples with density ranging from 8.45 – 8.50 were selected to study the rheological parameters at three different annular velocities (1.91, 2.86 and 3.82 ft/sec) and three hole angles (30^o, 45^o and 70^o) from vertical. A programme was developed using excel spreadsheet which could determine the rheological parameters and their effect on cuttings removal from non-vertical boreholes. Results showed that better sweep of drilled cuttings is favoured by increasing annular velocity and increasing hole angle. Both the apparent and effective viscosities should increase, power law flow index should be decreased while power law consistency index should be increased. The yield point and plastic viscosity values should all be high but done in such a way that they will result in low *YP*/*PV* ratios.

Keywords: Rheology, Cuttings Buildup, Rate of Penetration, Carrying Capacity, Slip Velocity

1 Introduction

Many materials of engineering interest must be handled and transported as slurries or suspensions of insoluble particulate matter. Transportation of cuttings in non-vertical boreholes is of no exception. Almost the same thing occurs whereby the cuttings act as the solids in the drilling fluid. In spite of the many technological advances that have accompanied the drilling of non-vertical boreholes, one significant remaining challenge is effective cuttings transport, particularly in deviated wells.
The transportation of cuttings during drilling has a major influence on the economics of the drilling process. Problems that can occur as a result of inefficient hole cleaning from cuttings include reduced weight on bit, reduced rate of penetration (ROP), increase pipe sticking and inability to attain the desired reach, extra cost because of the need of special additives in the drilling fluid, extra pipe wear, transient hole blockage which can lead to lost circulation and wasted time for wiper tripping. (Kelessidis, 2004).

Hole cleaning relying on viscous fluids in laminar flow for drilling, especially when using coiled tubing, has shown to be inefficient because of the inability to rotate the string to agitate the bedded/accumulated cuttings. Alternatively, a high fluid flow to induce turbulent flow regime is more effective for hole cleaning, but difficult to achieve because of high friction pressures in the drillpipe. Therefore a bed of cuttings is almost always present in non-vertical boreholes. Rheology which is the study of the flow and deformation of fluids is an important contributing factor to the above mentioned problems. Rheology describes the relationships between shear rate and shear stress. Pilehvari and Azar (1999), Azar and Sanchez (1997) state that fluid velocities should be maximized to achieve turbulent flow, and mud rheology should be optimized to enhance turbulence in inclined/horizontal sections of wellbore. The purpose of this paper is to investigate how rheological parameters influence the removal of cuttings in non-vertical boreholes.

1.1 Fluid Rheology

Rheology is the study of the flow and deformation of fluids. Deformation is a change in shape in response to an applied force, which can be tension, compression, shear, bending, or torsion. A force applied to an area is called a stress. The fluids are mainly liquids but also soft solids flowing under conditions in which they flow without deforming elastically may be included. Rheology comes from the Greek word "rheos" which means to flow. The rheological characteristics of fluid are important in evaluating its ability to perform a specific function. It describes the relationships between the shear rate and the shear stress that causes movement. The study of rheology shows how materials, particularly liquids, respond to applied stress. Drilling fluid with adequate low end rheology will form soft or no cuttings beds when the pump is off, minimises torque and drag while drilling, lessens the chance of becoming mechanically stuck and brings about easy logging and testing (Anon, 2009). Rheological models combine developments

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in the fields of particle settling and rheology to provide a useful tool for the planning of hole cleaning. Various models are used to describe the shear-stress versus the shear-rate behavior of drilling fluids. The most commonly used are the Power Law, Bingham Plastic, and Herschel-Bulkley (Dominique, 1990).

1.2 Theory of Cuttings Transport

The ability of a drilling fluid to transport cuttings to the surface is generally referred to as "carrying capacity". From an engineering point of view, cuttings transport is dependent on wellbore inclination, cuttings slip velocity, flow regime, rotary speed of the drill pipe, fluid rheology, fluid flow rate, rate of penetration, cuttings size and shape, wellbore geometry and other drilling parameters. Efficient hole cleaning is especially important in drilling non-vertical boreholes since problems can be worsen due to the smaller clearances between the drilling string and the wellbore. For an inclined well, the direction of cuttings settling is vertical, but the fluid velocity has a reduced vertical component. This decreases the mud's capability to suspend drilled cuttings. At a high angle of inclination a particle that sediments through the mud has a short distance to travel before striking the borehole wall. Once it reaches the wall, the particle has little chance to be entrained because local fluid velocities near the wall are very low and insufficient to re-entrain the particle into the flow. Consequently, the residence time of the particle in the annular space increases significantly resulting in a higher concentration of cuttings in the wellbore. This brings about formation of a cuttings bed that creates operational problems (Sifferman and Becker, 1990).

2 Resources and Methods Used

In order to understand the effect of rheological parameters on cutting transportation in non-vertical wellbores, this section provides to some vital relations as far as cutting transportation is concerned and presents the method used in carrying out this work.

2.1 Annular Velocity, (AV) and Critical Annular Velocity (AVc)

These parameters are paramount in the hole cleaning technology as they influence the efficiency of the drilling process. The annular velocity (ft/min), can be calculated by Equation 1:

$$AV = \frac{24.5Q}{d_h^2 - d_p^2} \tag{1}$$

where *AV is* annular velocity, ft/min; *Q* is flow rate, gal/min; d_h is inside diameter of casing or hole size, in. and d_p is outside diameter of pipe, tubing or collar, in..

The critical annular velocity can also be obtained by the expression Equation 2:

$$AVc = (X)^{1+(2-n)} \tag{2}$$

where

$$X = \frac{81600(K)(n)^{0.387}}{(d_h - d_p)^n MW} \tag{3}$$

where *AVc* is critical annular velocity, ft/min; *K* is power law consistency index, lbf-secn/ft^2; *n* is power-law flow index, dimensionless and *MW* is mud weight, ppg.

2.1.1 Cuttings Slip Velocity, Cuttings Net Rise Velocity and Transport Efficiency

Drilled cuttings have the tendency to fall down (slip) through the fluid medium at a velocity referred to as the cutting slip velocity (V_s). For the fluid to be lifted to the surface, the fluid Annular Velocity (*AV*) must exceed the cutting slip velocity (V_s). The relative velocity between fluid annular velocity and cutting slip velocity is known as the cutting net rise velocity (V_t). The cutting slip velocity, (ft/min) is given by Equation 4:

$$V_s = \frac{(DensP - MW)^{0.667} \times 175 \times DialP}{MW^{0.333} \times \mu^{0.333}} \tag{4}$$

where *DensP* is cutting density, ppg; *DiaP* is cutting diameter, in., *MW* is mud weight, ppg and μ is viscosity in cp given by Equation 5.

$$\mu = \left(\frac{2.4AV}{d_h - d_p} \times \frac{2n+1}{3n} \right)^n \times \left(\frac{200K(d_h - d_p)}{AV} \right) \tag{5}$$

The cuttings net rise velocity (V_t) is given by Equation 6:

$$V_t = AV - V_s \tag{6}$$

The cuttings transport efficiency (E_t), which is the ratio of cuttings transport to annular velocity is more important than an actual cuttings transport value and it is given by Equation 7:

$$E_t = \frac{V_t}{AV} \times 100 = \left(1 - \frac{V_s}{AV}\right) \times 100 = 100R_t \tag{7}$$

where R_t is cuttings transport ratio.

2.1.2 Axial and Radial Components of Particle Slip Velocity

The behaviour of cuttings in inclined wells is very different from that in vertical wells. In a vertical hole, slip velocity acts parallel to the axis of the hole. In inclined holes, slip velocity has two components, an axial one and a radial one. According to gravity laws, only the axial component of the slip velocity exists in the case of a vertical annulus and it is given by Equation 8:

$$V_s = V_{sa} \tag{8}$$

with the radial component of the slip velocity expressed by Equation 9.

$$V_{sr} = V_s Sin\theta \tag{9}$$

where V_s is cuttings slip velocity, ft/min; V_{sa} is axial component of particle slip velocity, ft/min; V_{sr} is radial component of particle slip velocity, ft/min and θ is hole angle.

This situation is shown in Fig. 1.

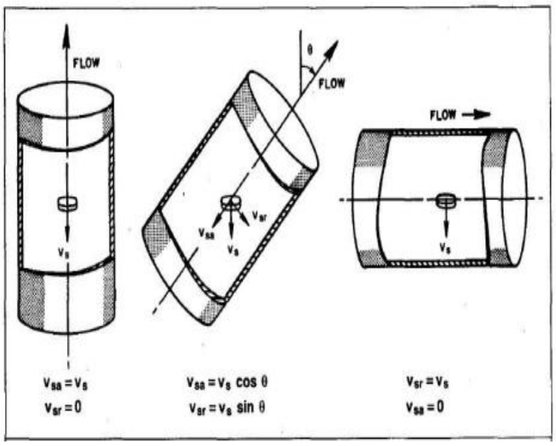


Fig. 1 Particle Settling Velocity in an Inclined Annulus (Okrajni and Azar, 1986)

2.1.3 Cuttings Concentration, (vol %)

Due to the slip velocity of cuttings in the annulus, the concentration of cuttings in the annulus depends upon the transport efficiency as well as the volumetric flow rate and the rate at which cuttings are generated at the bit (ROP and hole size). Experience has shown that cuttings concentration in excess of five (5) volume % can lead to a pack-off, tight hole, or stuck pipe (Anon, 2006). When drilling in soft formations, where pipe connections in the drill string are made as rapidly as possible, the cuttings concentration may easily exceed 5%, if ROP is uncontrolled. (Anon, 2006). The cuttings concentration (C_a) is calculated by Equation 10:

$$C_a = \frac{(ROP)d_h^2}{14.71(E_t)(Q)} \times 100 \tag{10}$$

where E_t is cuttings transport efficiency, % and Q flow rate, gal/min.

A programme was developed using Microsoft excel where the above given relations were coded. The other variables used in this study are presented in Table 1. Power law fluid was used in this study and twelve mud samples were obtained from literature with their fann viscometer dial readings (Table 2). The rheological parameters; power law flow index, consistency index, plastic viscosity (PV), mud yield point (*YP*), *YP*/*PV* ratio, apparent viscosity, and effective viscosity were calculated. The study considered three annular mud velocities (1.91, 2.86, 3.82 ft/sec) and three hole inclinations (30^o, 45^o and 70^o) from vertical. The programme could determine the volume of cuttings generated and the effect of rheology on the drilling fluid as a result of the cutting concentrations.

Table 1 Values of other Variables used in the Annulus Cleaning Study

Parameters	Value
Inside diameter of casing or hole size (d_h)	5 in.
Outside diameter of pipe or tubing (d_p)	2 in.
Diameter of cuttings (DialP)	0.25 in.
Density of cuttings (DensP)	22 ppg
Rate of Penetration (ROP)	50 ft/hr

3 Results and Discussion

3.1 Effects of Rheological Parameters on Critical Annular Velocity

Plots of critical annular velocity versus some of the major rheological parameters were made from which a lot of valuable information can be deduced. For effective cuttings lift and transportation, the critical annular mud velocity should be greater than the settling velocity of the largest cutting. Low critical annular velocity will lead to an undesirably high concentration of cuttings in the annulus.

In Fig. 2, observation of the trend line shows that, an increase in the flow index (*n*) increases the critical annular velocity. The amount of cuttings concentration in the annulus will therefore be on the decrease as the value of *n* increases because of the tendency of *n* to cause an increase in the fluid velocity in the annulus.

Table 2 Mud Parameters used for the study

Mud	Density	Fann Rotary Speed, rev/min (Shear Rate, seconds^{-1})						AP (cp)	PV (cp)	YP (lbf/100 ft^2)	YP/PV	n_a	Ka (lbf sec^n)/ft^2
		θ3	θ6	θ100	θ200	θ300	θ600						
1	8.45	1	1	8	14	18	30	15	12	6	0.5	0.6276	1.8357
2	8.45	1	1	7	10	12	18	9	6	6	1.0	0.5396	2.1192
3	8.45	1	2	6	8	9	12	6	3	6	2.0	0.4771	2.3465
4	8.45	1	2	14	24	30	50	25	20	10	0.5	0.7386	1.5318
5	8.45	1	2	12	17	20	30	15	10	10	1.0	0.6505	1.7684
6	8.45	2	3	11	14	15	20	10	5	10	2.0	0.4375	5.0060
7	8.50	2	3	23	38	48	80	40	32	16	0.5	0.6901	3.3156
8	8.50	2	4	18	28	32	48	24	16	16	1.0	0.6021	3.8277
9	8.50	4	6	17	23	24	32	16	8	16	2.0	0.3891	10.835
10	8.50	2	6	26	45	60	100	50	40	20	0.5	0.7386	3.0636
11	8.50	6	8	21	34	40	60	30	20	20	1.0	0.4120	15.658
12	8.50	7	10	22	29	30	40	20	10	20	2.0	0.3160	21.362

Fig. 3 shows how the power law consistency index (*K*) influences the critical annular velocity which aids in efficient hole cleaning process. According to this research, the effect of consistency index corrected for the annulus on the critical annular velocity is minimal as increasing values of *K* increase critical annular velocity but only slightly (see trend line).

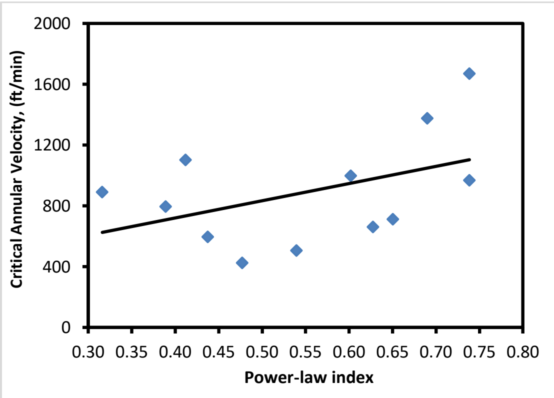


Fig. 2 Effect of Power Law Index on Critical Annular Velocity

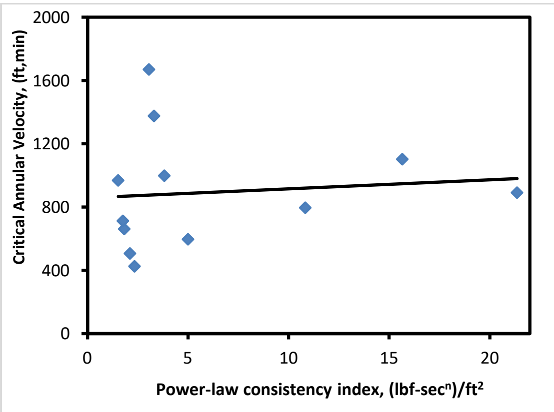


Fig. 3 Effect of Power Law Consistency Index on Critical Annular Velocity

The impact of plastic viscosity on the critical annular velocity is also is depicted in Fig. 4. The critical velocity at the annulus increases significantly with an increase in plastic viscosity. Therefore, to ensure effective and successful cuttings removal from the annulus the plastic viscosity should be increased which will indirectly increase the critical annular velocity required to accomplish the hole cleaning purpose.

The effect of muds yield point on critical annular velocity is presented in Fig. 5 and the critical annular velocity can be seen to be favoured by increasing yield point.

Due to the reason of plastic viscosity and yield point having some relations, their combined effect on the critical annular velocity was therefore investigated and the presentation is as shown in Fig. 6. Here, when the *YP*/*PV* ratio is on the rise, critical annular velocity decreases. This means that the increase in both the plastic viscosity and the yield point should be carefully done in such a way that they will result in low *YP*/*PV* ratios. Thus, their combination should bring about a good cuttings transportation.

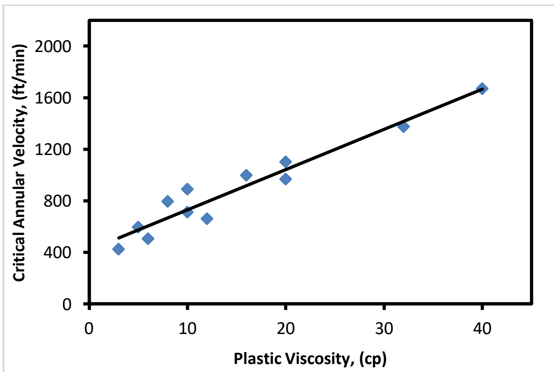


Fig. 4 Effect of Plastic Viscosity on Critical Annular Velocity

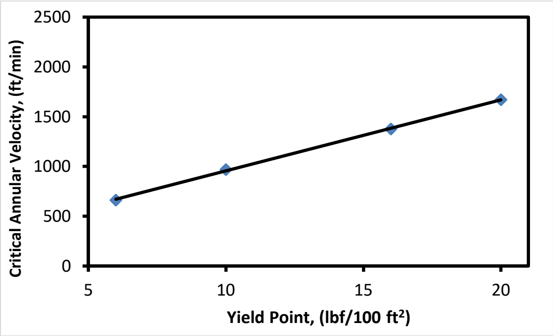


Fig. 5 Effect of Yield point on Critical Annular Velocity

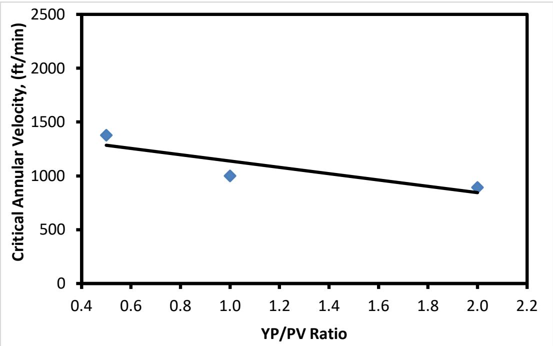
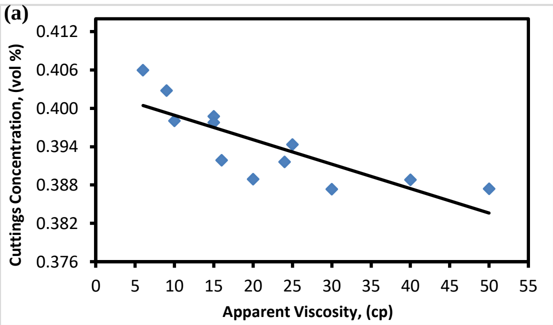


Fig. 6 Effect of YP/PV Ratio on Critical Annular Velocity

3.2 Effects of Rheological Parameters on Cuttings Concentration

Figs. 7 (a) and (b) are plots of cuttings concentration versus apparent viscosity. Both plots show that, cuttings concentration declines with increasing value of apparent viscosity. Again, it was observed that, Fig. 7 (b) which has a lower annular mud velocity recorded higher values of cuttings concentration compared to Fig. 7 (a). For efficient hole cleaning process, it is therefore important to resort to high apparent viscosity values while maintaining a high annular mud velocity.



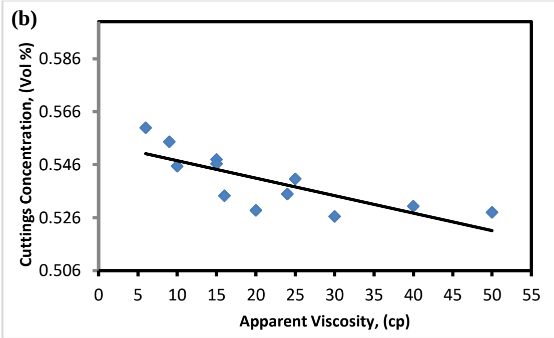


Fig. 7 Annular Cuttings Concentration Effect on Apparent Viscosity at θ = 30: (a) AV= 3.82 ft/sec (b) AV = 2.86 ft/sec

Figs. 8 presents the impact of effective viscosity on cuttings concentration at different annular velocities. At 3.82 ft/sec mud velocity lower cutting concentrations were achieved compared to flowing the drilling mud at 2.86 ft/sec mud velocity. Again, improving upon the effective viscosity of the mud ensured decreasing cuttings in hole. Hence, increasing effective viscosity and increasing annular mud velocity help in promoting good and efficient cuttings removal.

The combined effect of hole inclination and rheology on cuttings accumulation in the annulus are also presented in this research.
Fig. 9 presents the effects of the power-law flow index on the cuttings concentration at the selected annular mud velocities for θ = 30^o from vertical. It can be seen that the higher the annular mud velocity, the lower the cuttings concentration. Increasing values of the power-law flow index will also lead to an increase in cuttings concentration but only slightly. Similar trends were obtained for hole angles 45^o and 70^o from vertical.

Fig. 10 also presents how the power-law flow index affects cuttings concentration taken into account all the hole angle considered in this work. The plot at θ = 70^o from vertical gave the lowest amount of cuttings concentration followed by that at θ = 45^o while θ = 30^o gave the highest.

The combined effect of consistency index on cuttings concentration for hole angle of θ = 30^o from vertical the is also depicted in Fig. 11. Cuttings concentration in this case reduces with increasing consistency index. Also the annular mud velocity greatly influences the cuttings concentration.

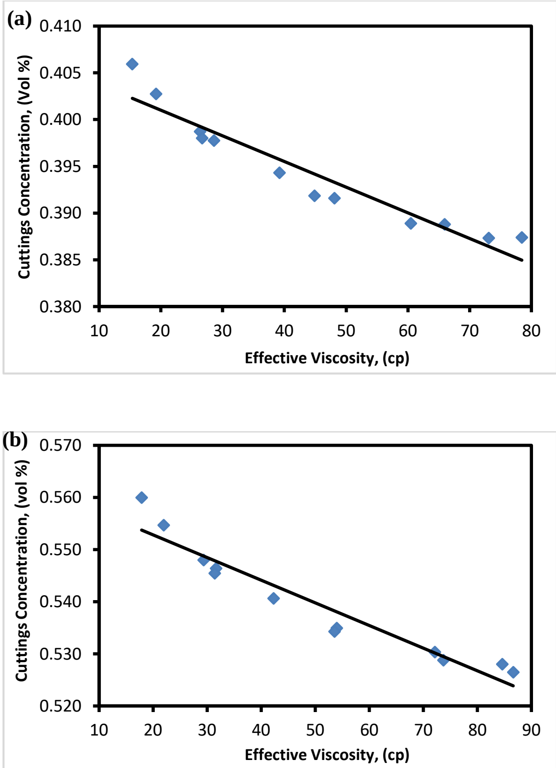


Fig. 8 Annular Cuttings Concentration Effect on Effective Viscosity at θ = 30: (a) AV= 3.82 ft/sec (b) AV = 2.86 ft/sec

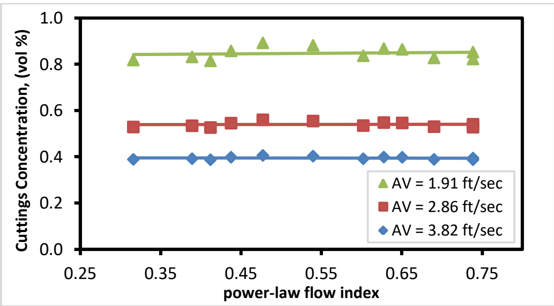


Fig. 9 Combined Effect of Power-Law Flow Index on Cuttings Concentration (θ =30°)

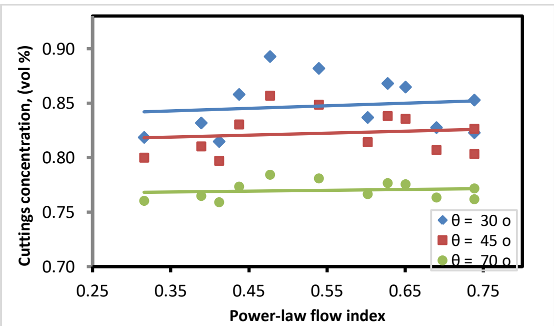


Fig. 10: Annular Cuttings Concentration Effect on Power Law Flow Index at AV= 1.91 ft/sec and θ = 30°, 45°, 70°

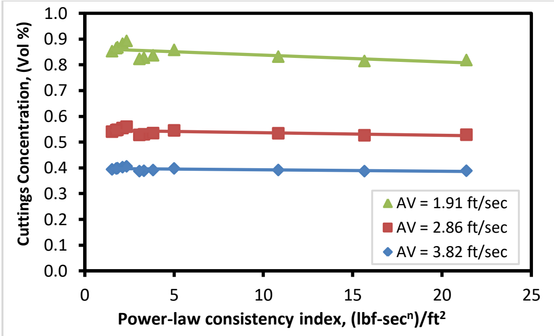


Fig. 11 Combined Effect of Power Law Consistency Index on Cuttings Concentration for Hole Angle of 30°

The higher the annular mud velocity, the lower is the volume of cuttings generated. Similar plots were obtained for θ = 45° and θ = 70°.

With regards to how the power-law consistency index affects the cuttings concentration at a given annular velocity and varying hole angles, this can be seen in Fig. 12 above. The cuttings concentration again in this case decreases as the consistency index (K_a) increases no matter the angle of inclination. An increasing value of K_a is therefore required to ensure successful cuttings transportation.

Fig. 13 also presents the effect of plastic viscosity on the cuttings concentration. In this figure, the cuttings concentration declines as the plastic viscosity increases. By combination the information obtained from this figure and that from Fig. 4, it is obvious that an increasing critical annular velocity together with increasing plastic viscosity will bring about an excellent hole cleaning.

The effect of yield point (*YP*) on the cuttings concentration was also investigated. Fig. 14 shows how C_a changes with *YP* at different hole angles. It can be deduced from this figure that higher values of *YP* will be advantageous to limiting cuttings buildup in the annulus thereby enhancing efficient hole cleaning.

The combined effect of both yield point (*YP*) and plastic viscosity (*PV*) on the amount of cuttings concentration was therefore investigated. Relatively high plastic viscosities considerably reduce the *YP*/*PV* ratio. From the plots in Fig. 15, it can be shown that the higher YP/PV ratios, contribute to increasing cuttings concentration and vice versa. This is true for all the angle of inclinations considered in this study.

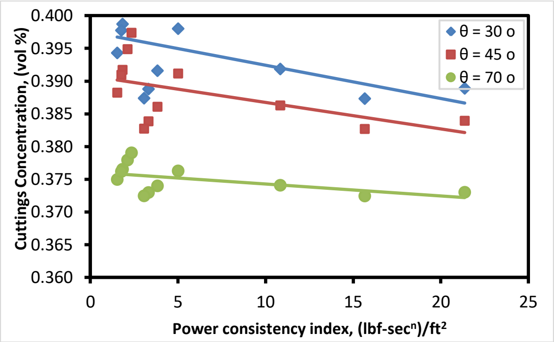


Fig. 12 Annular Cuttings Concentration Effect on Power Consistency Index at AV= 3.82 ft/sec and θ = 30°, 45°, 70°

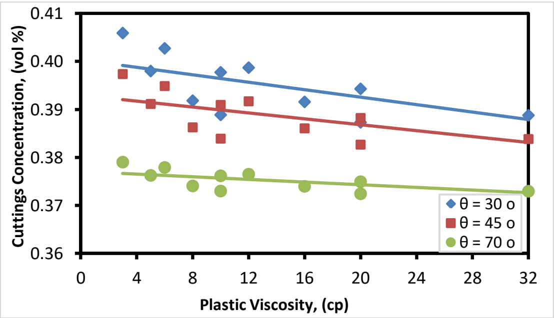


Fig. 13 Annular Cuttings Concentration Effect on Plastic viscosity at AV= 3.82 ft/sec and θ = 30°, 45°, 70°

Because of the influence that *PV* has on *YP*/*PV* ratio, the *PV* should increase with respect to *YP* so as to reduce the accumulation of cuttings in the annulus. The *YP*/*PV* ratio should be low.

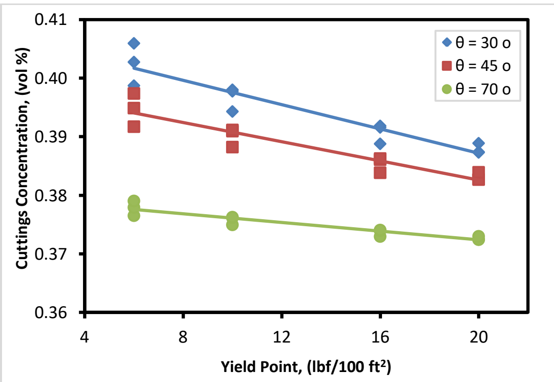


Fig. 14 Annular Cuttings Concentration Effect on Yield Point at AV= 3.82 ft/sec and θ = 30°, 45°, 70°

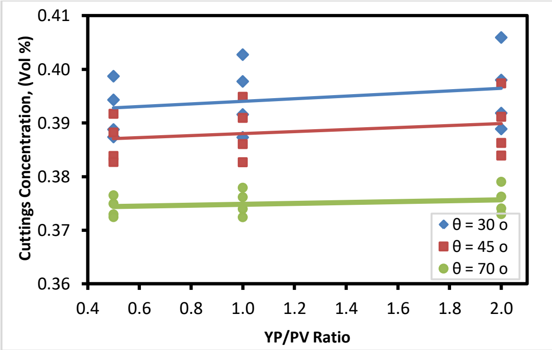


Fig. 15 Annular cuttings Concentration Effect on *YP*/*PV* ratio at AV= 3.82 ft/sec and θ = 30°, 45°, 70°

In Fig. 16, we have plots of cuttings concentration versus hole inclination. Muds 1 and 12 were used to illustrate this point. It can be deduced from Fig. 16 that, the cuttings concentration generated is highest at 30°, followed by at 45° with 70° hole angle recording the least. This means that the more horizontal the wellbore becomes (θ nearing 90°) the easier will be the cuttings transport due to low cuttings accumulation. Similar trends were obtained for the other annular mud velocities, 1.91 and 2.86 ft/sec. Higher flow rates will therefore be needed for lower hole angles in the range of 30° – 45°.

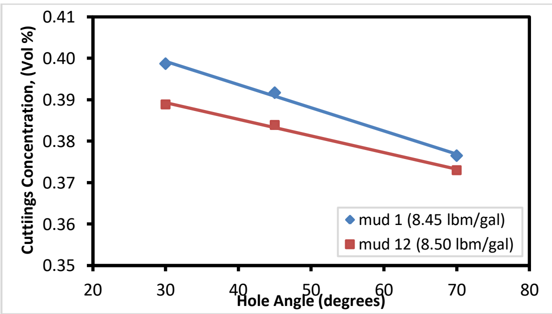


Fig. 16 Cuttings Concentration vs. Hole Angle for Annular Velocity of 3.82 ft/sec

4 Conclusions

The findings of this research are relevant in the transportation of drilled cuttings in inclined wellbores. The following conclusions can be drawn from this study:

(i) In the study and assessment of drilling-fluid cuttings transport in non-vertical boreholes, the annular cuttings concentration (vol. %) should be considered first. Its value gives the indication of which rheological parameter to manipulate to bring about a successful cuttings removal.

(ii) For efficient hole cleaning process, the power-law flow index, consistency index, yield point, plastic viscosity, and *YP*/*PV* ratio should all be considered and used in the evaluation and assessment process.

(iii) In laminar flow, the annular cuttings concentration is lower for higher *YP*/*PV* ratios. This is true for the entire range of hole inclinations investigated in this study.

(iv) In laminar flow, increasing values of mud yield point result in decreasing the annular cuttings concentration. The same situation applies to increasing plastic viscosity.

(v) Very high cuttings concentrations were recorded at hole inclination in the range of 30^o to 45^o. This normally occurs when the annular flow rates are relatively low (0 – 90 gpm).

(vi) In laminar flow, the effects of mud yield value and *YP*/*PV* ratio are more pronounced for lower annular mud velocities. Thus at these velocities, higher annular cuttings concentrations were recorded.

(vii) The effect of mud flow rate has great influence during hole cleaning in non-vertical boreholes. Higher flow rates increases the critical annular velocity which in turn brings about decreasing cuttings concentration.

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