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ASSESSMENT OF DRILL CUTTINGS BEHAVIOUR IN WELLBORE WASHOUTS

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ABSTRACT

Accumulation of cuttings in washout sections due to low velocity of drilling fluids in inclined wellbores poses a general challenge to the drilling industry. In this research, the behavior of cuttings is examined while fluid is used to clean the beds in the washouts. In order to verify this, a 3m flow loop was constructed to perform an experiment which set the annulus angle at 8^o to the horizontal using actual drill cuttings diameters of 0.1-1mm. The bed heights and flow rates of five different mud rheologies were measured in the loop. Water and aqueous solutions of Hydroxyethyl Cellulose (HEC) were used for cleaning the sand beds. The results show that at low flow rates, the bed heights remain almost constant with time showing little or no decrease in bed heights in all washout diameters considered with the opposite being the case for high flow rates. An equilibrium bed height based on an optimum flow rate should be maintained in a wellbore washout so that the cuttings in such areas could serve as a fill up to maintain equal diameter throughout the wellbore. Cuttings removal in the washouts is easier with turbulent flow than with laminar flow.

Keywords: Drill Cuttings, Bed height, Hydroxyethyl Cellulose, Wellbore Washouts, Mud Rheology

INTRODUCTION

Cleaning of inclined wellbores is a general challenge to the oil and gas industry. A more specific challenge in inclined wells is the accumulation of cuttings in washouts sections due to low velocity of drilling fluids. Accumulation of cuttings in washouts not only cause holes to be inadequately cleaned but can also cause restrictions which may, lead to increase in hook load, large over pulls and finally to stuck pipe. These restrictions are experienced during tripping and cause time losses and even for small restrictions, the operator may choose to stop to rectify the problem, hence the need to examine drill cuttings behavior and prevent time losses.

One hypothesis in the present investigation is that many of these problems stem from the fact that despite drilling fluid circulation, cuttings tend to accumulate in the washout sections of the hole and when tripping through them, the bottom hole assembly is jammed tight in the wellbore. Washouts can be seen to be enlargement of holes or wellbores during drilling operations. One known fact about washouts is that cuttings tend to accumulate in washout sections of the hole when mud is circulated. Reference [1] defined a washout as an enlarged region of a wellbore. Other restrictions during tripping are underguaged hole, accumulation of cuttings in the hole, high doglegs in wellbores, tripping into a hole with a bit size larger than the wellbore etc.[2].

Washouts can be explained primarily by two mechanisms: borehole collapse of a portion of the wellbore due to insufficient mud weight and/or hole erosion due to improper mud chemistry design[1]. Reference [3] holds the view that washout can be caused by High Weight on Bit (WOB) in laminated formations, Hydraulic and mechanical erosion of weakened formations and Swelling of shale and clay as it contacts freshwater thus weakening the formation. This same view was also held by [4].

Causes of Washouts

Reference [5] had a different point of view on this matter. They claimed that the causes for borehole washouts are numerous and that annular velocity is falsely blamed for the erosion. They added that in unconsolidated sands, decreasing the flow rate does lead to a better gauge hole. Besides, decreasing the flow rate decreases the annular velocity but it also decreases the nozzle velocity, the hydraulic impact, and the hydraulic horsepower at the nozzles. Looking at this from a chemical viewpoint, [6] pointed out that the presence of salt can result either in an enlarged hole or an undergauged hole. He added that hole enlargement occurs when the drilling mud contains a water phase having a salinity less than the saturation point. This causes the salt to dissolve in the water, washing out the hole. To keep this from happening, he suggested that operators can use non-dissolving salt water or oil base muds.

References [5][7] viewed borehole washouts or hole enlargement as a result of hole instability that may be caused by one or more of the following: state of stress underground, thermal stresses and stresses induced by pressure gradient between formation pore pressure and wellbore pressure associated with the flow of formation fluid to the wellbore. They said that it can also be due to chemical reactions between well-bore fluid and its filtrate with formation rock and its fluids content, mechanical drag on well-bore wall caused by drill string and hydraulic drags caused by annular pressure losses and surge pressures. Based on field experience in Arkoma Basin on air/gas drilling operations, [8] found out that, wellbore washouts occur as a result of both erosion (drill string wearing away the rock) and sloughing.

Effects of Washouts on Wellbore Drilling Operations

The effects of washouts on wellbore drilling operations as pointed out by [2][10][11][15][17] are stuck drill pipe, increased annular pressure resulting in wellbore fracture and lost circulation and low flow velocity causing bad hole cleaning. It also causes difficulty in tripping which may lead to sidetrack or plugging and poor cementing, perforating, sand control, production and stimulation problems.[13][16].

Reference [5] puts forward that washouts result in difficulty providing adequate hole cleaning capability and excess cuttings can increase bottom hole pressure, causing lost circulation and/or stuck pipe. Wellbore washouts also cause cuttings and drilling fluid disposal costs to increase. In Reference [9] under certain conditions, salt will dissolve and result in borehole enlargement which would cause unpredictable directional tendencies, poor Bottom Hole Assembly (BHA) performance and stability issues.

Materials and Methods

The experimental work was used to study the behaviour of cuttings in washout sections of inclined wellbores and in unaffected sections as drilling fluid is being circulated. The drilling fluid consists of either water or Hydroxyethyl cellulose (HEC) based drilling fluid.

HEC is named after its two components: cellulose and hydroxyethyl side chains. Cellulose is a water insoluble, long chain molecule consisting of repeating anhydroglucose units. HEC is manufactured when purified cellulose is reacted with sodium hydroxide to produce swollen alkali cellulose. By reacting the alkali cellulose with ethylene oxide, a series of hydroxyethyl cellulose ethers are produced [12][14].

Table 1: Typical Properties of Aqueous Solutions of Hydroxyethyl Cellulose

Property	Value
pH	6-7
Appearance	White coloured free flowing powder
Bulk density	0.3-0.6 g/cm^3
Specific gravity at 20°C	1.3-1.4

Flow Loop Description

The experimental apparatus as shown in Figure 1 consists of a 3m long transparent PVC pipe which ensures flow visualization represents the wellbore and has 1 inch outer diameter. The washout section is the middle of the pipe and was varied in terms of the outer diameters of 1.5 inches and 2 inches.

The flow loop is supported by a structure that can be tilted from horizontal, hence various inclinations from horizontal can be studied (maximum inclination ~ 15 degrees). There is a plastic tank, holding about 100 litres of mud. The flow is achieved by gravity using a high head pressure resulting from placing the mud tank at a height of 3 m above the ground. The flow is regulated with a simple open and close valve capable of delivering different flow rates depending on adjustment. The flow rate is measured by calculating the volume of mud in the receiving tank and dividing it by the time it takes the volume to accumulate in the tank meter. Viscosity of mud is measured with a viscometer.

The cutting is manually filled into the PVC pipe to about 60 percent. Fig. 1 shows the flow diagram of the test loop.

Test Apparatus Design

The test apparatus was designed and constructed in accordance with the following requirements: annular-flow steady state conditions must prevail in every test case and the apparatus must allow the selection of the flow rate and well inclination that must be representative of average field conditions.

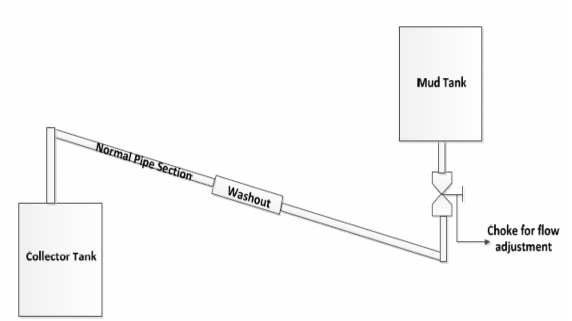

Figure 1: Flow Diagram of Test Loop

To meet the above requirements, a test apparatus was designed and constructed. It consisted of the following major components:

- An independent means of circulating the mud
- A section of annulus with a washout in the middle
- A reliable means of controlling liquid flow rate
- A means of varying the inclination angle of the test section.

Test Procedure

Once the operational parameters (geometry, inclination, fluid and solid properties) are chosen, the following procedure was adopted:

1. Fill the test section with 60% cuttings to form a bed of constant height along the test section. Fluid flow rate should be minimal and constant;
2. Increase fluid flow rate to begin bed erosion. When steady state is reached (no more solids removal), record bed perimeter, transient time and observe removal flow patterns.
3. Repeat step 2 for different fluid flow rates

Results and Discussion

Drilling Fluid Rheology: The experimental findings reported here were obtained from water and 2 grams of hydroxylethyl cellulose (HEC) drilling fluid for every 1 liter of water giving plastic viscosities of 7cp, 15cp, 20cp and 30cp at 300 rpm and increased stepwise to obtain higher viscosities. These concentrations were used to provide comparable effective viscosity to that which would be anticipated in a hole section using a field mud. Rheologically, HEC polymer-based drilling fluid behaves as a pseudo-plastic fluid. Since HEC thickens with time at the bottom of the tank, its rheology had to be measured every 5 to 10 minutes of test duration in order to maintain a reasonable degree of consistency in the fluid's rheology while the test is on.

Table 2: 0.5% Liquid HEC polymer fluid

RPM	600	300	200	100	6	3
γ (s^{-1})	1022	511	340	170	10	5.1
Θ	13.5	7.1	5	3	0.3	0.2
τ (Ib/100ft²)	14.3	7.53	5.3	3.18	0.32	0.21
τ(Pa)	6.85	3.6	2.54	1.52	0.15	0.1

Table 3: 1% Liquid HEC polymer fluid

RPM	600	300	200	100	6	3
γ (s^{-1})	1022	511	340	170	10	5.1
Θ	26	15.2	10.7	5.8	0.6	0.38
τ (Ib/100ft²)	27.6	16.1	11.3	6.15	0.64	0.4
τ(Pa)	13.2	7.7	5.4	2.94	0.31	0.19

Table 4: 1.5% liquid HEC polymer fluid

RPM	600	300	200	100	6	3
γ (s^{-1})	1022	511	340	170	10	5.1
Θ	31.9	19.8	12.7	7	2	1.8
τ (Ib/100ft²)	33.8	21	13.5	7.42	2.1	1.91
τ(Pa)	16.2	10.1	6.5	3.6	1.01	0.91

Table 5: 2% Liquid HEC polymer fluid

RPM	600	300	200	100	6	3
γ (s^{-1})	1022	511	340	170	10	5.1
Θ	43.2	30.1	20.2	12	4	3
τ (Ib/100ft²)	45.8	31.9	21.4	12.7	4.2	3.2
τ(Pa)	21.9	15.3	10.2	6.1	2	1.5

Five different flow rates of drilling fluid between 50-100 L/min were used. Throughout the range of annular velocities studied with HEC the flow regime was laminar and turbulent with water. The test was carried out at a constant inclination angle of 8 degrees to the horizontal. The range of cuttings sizes used was 0.1-1.0 mm in diameter.

Test Matrix

In this matrix we have 11 test sets, every test set contain five test elements that are carried out at different flow velocities. A total of 55 different tests were performed using solutions of Water and HEC, at different concentrations, to represent the drilling fluids and particles of sandstone cuttings of diameters 0.1-1 mm. The fluid flow velocity varies between the minimum limit, which is the critical velocity for a given sand bed, and the maximum limit that is the velocity at which the erosion time is measured visually with acceptable degree of accuracy. Table 6 shows the fluid systems used for the comparison. Readings and rheological parameters are shown in Table 7.

Table 6: Fluid systems used in comparison

Description	**Base case**	**Fluid A**	**Fluid B**	**Fluid C**	**Fluid D**
Fluid type	**Water**	**HEC based (thin)**	**HEC based (average)**	**HEC based (average)**	**HEC based (thick)**
n	1	0.93	0.78	0.68	0.52
k(N-s^n / m^2)	1	0.011	0.059	0.145	0.59
Density(kg/L)	1	1.006	1.01	1.12	1.19
μ_a (cp) @ 511s^{-1}	1	7	15	20	30

Table 7: Test matrix for cuttings transport in pipe at 8 degrees inclination

		Mud Flow Rate (L/min)				
Pipe type		50	60	70	80	100
Lean pipe	**Mud Viscosity (cP)**	**Stabilized Bed Height (cm)**				
	1	1.5	1.5	1.3	0.10	0.0
	7	1.5	1.49	1.3	0.05	0.0
	15	1.5	1.48	1.2	0.02	0.0
	20	1.5	1.48	1	0.01	0.0
	30	1.5	1.47	0.8	0.01	0.0
1.5 in OD						
	1	2.28	2.28	2.2	1.15	0.4
	15	2.28	2.28	2.1	0.75	0.2
	30	2.28	2.28	1.8	0.5	0.1
2 in OD						
	1	3.0	3.0	2.6	1.5	0.90
	15	3.0	2.9	2.2	1.2	0.80
	30	3.0	2.7	2.0	1.0	0.68

The results obtained are categorized into two parts: cuttings bed height as a function of time and bed height as a function of fluid viscosity with washout diameter variations.

(a) Cuttings Bed Height as a function of Time

Figs. 2 to 4 shows the results for cuttings height as a function of flow time. It is observed that at low flow rates, the bed heights remain almost constant with time showing little or no decrease in bed heights in all washout diameters considered. The opposite is the case with high rates of flow; it is observed that the height of the cuttings decreases considerably with time in all washout diameters considered.

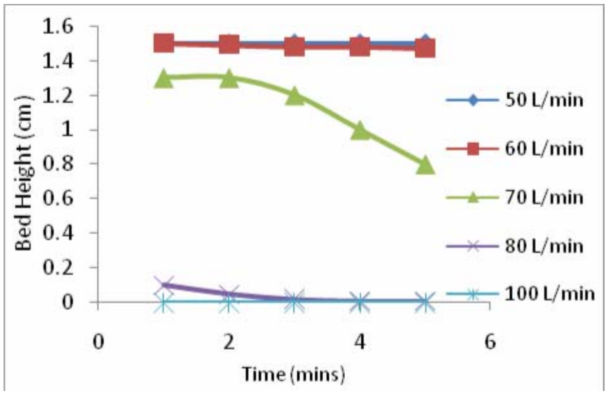

Figure 2: Bed Erosion Curves for Variable Flow Rates in Lean Pipe.

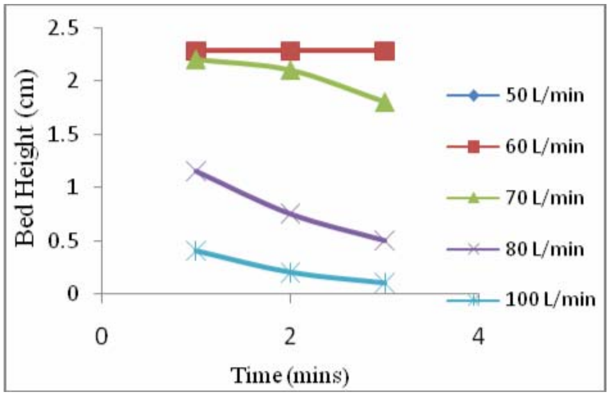

Figure 3: Bed Erosion Curves for Variable Flow Rates in 1.5 inch Washouts.

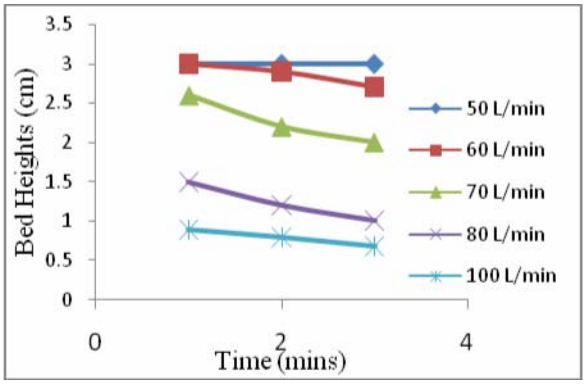

Figure 4: Bed Erosion Curves for Variable Flow Rates in 2.0 inch Washout.

(b) Bed Height as a function of Fluid Viscosity with washout Diameter variations

Figs. 5 to 7 show graphical interpretation of the results obtained when fluids of different viscosities were used to clean the beds. The values used for the curves were converted from cuttings bed heights to dimensionless bed height which is the ratio of the measured bed height to the initial height of cuttings in the test section. In all the different cases of washout diameters considered, the pattern of the curves obtained looked similar though one feature observable is that as the diameter of the washout increased, the higher the cuttings bed height in them. This can be attributed to the fact that with larger diameters, low fluid velocities would prevail and hence the tendency of cuttings accumulation is inevitable. The fluids with high viscosities tend to be effective in moving cuttings at low flow rates but water was only effective in cleaning the beds mainly at high flow rates.

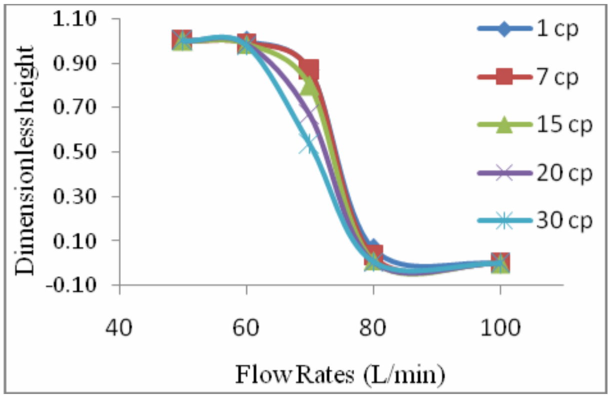

Figure 5: Dimensionless Bed Height vs. Flow Rates in Lean Pipe.

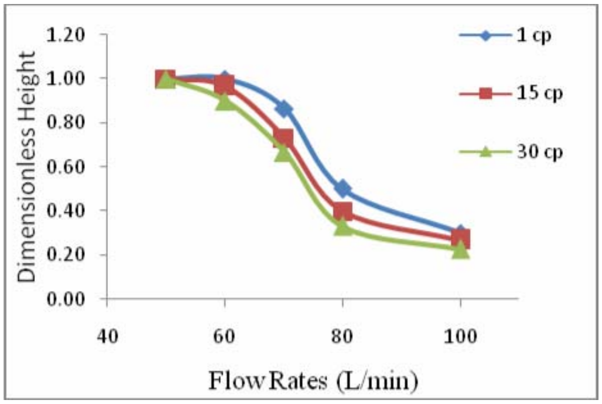

Figure 6: Dimensionless Bed Height vs. Flow Rates in 1.5 inches Washout.

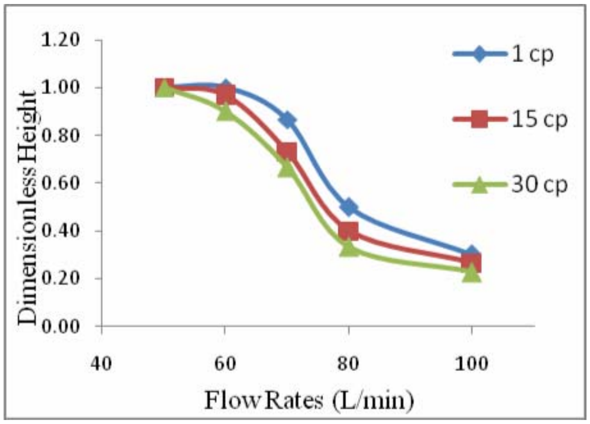

Figure 7: Dimensionless Bed Height vs. Flow Rates in 2.0 inches washout.

The drilling mud flow rate is a major factor controlling the formation of cuttings bed height. As shown in Figs. 2 to 4, higher flow rates results in lower cuttings bed height. For complete removal of cuttings, a much higher flow rate is required when using water 100 L/min ($1.667*10^{-3}$ m^3/s) is preferred to that of the thick mud 70 L/min ($1.167*10^{-3}$ m^3/s) and the critical flow rate for the thin mud 80 L/min ($1.33*10^{-3}$ m^3/s) is in between the thick mud and the water.

Bed Erosion with Water Flow

For the particular test reported here, there were two beds of solids formed in the lean pipe and the washouts approximately 1.5 cm, 2.3 cm and 3 cm high respectively. There was no bed erosion at a water flow rate of 50 L/min ($0.833*10^{-3}$ m^3/s). At 70 L/min ($1.167*10^{-3}$ m^3/s) erosion started on both beds and almost at the same time. It was observed that erosion occurred from the front of the bed, where the water impinges on the full height of the solid bed. This is as shown in Figure 8.

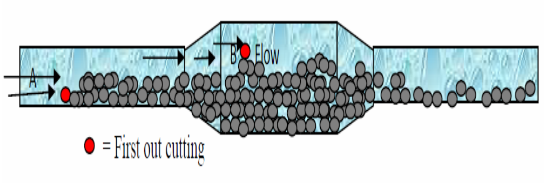

Figure 8: Water Erosion Mechanism

At 60 L/min ($1.0*10^{-3}$ m^3/s), the mean velocity in the lean pipe just before the bed (region A) is 0.04 m/s, giving a Reynolds number of 1.105, computed from the equation:

$$R_e = \frac{\rho V d_h}{\mu} \tag{1}$$

Where V is the liquid velocity, ρ the liquid density, $d_h = d_o - d_i$, the hydraulic diameter of the annulus and μ the liquid viscosity. For bed heights of 2.3 cm and 3cm in two cases of the washout (region B), the liquid flow area is 0.0574 m^2, 0.075 m^2 the hydraulic diameter is d_h = 0.0380 m, 0.050 m respectively and the mean liquid velocities above the bed for the flow rate of 60 L/min ($1.0*10^{-3}$ m^3/s) were 0.029 m/s, 0.022 m/s, giving a Reynolds number of 0.8446, and 1.111 respectively. Although flow is more turbulent above the bed in the washout region, erosion with water is observed to occur first from the front of the bed.

Bed Erosion with (HEC) Slurries Flow

For the thin HEC fluid (μ=7 cp), erosion of the 1.5 cm bed height in the lean pipe started from the top of the bed at flow rates just above 70 L/min. The mean velocity in washout region (region B) is 0.044m/s, 0.033m/s the hydraulic diameters being 0.038 m, 0.05 m respectively for the two washouts indicating laminar flow with Reynolds numbers 0.243 and 0.237 respectively

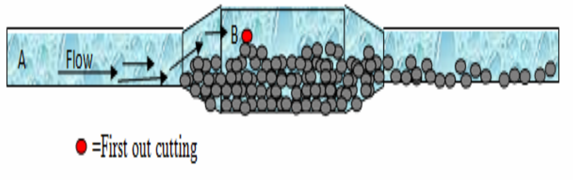

Figure 9: Viscous Fluid Erosion Mechanism

Compared to the case of water flow, a big difference is observed on the erosion mechanism. The particles are now eroded from the top of the bed and not from the front as shown in Figure 9. Furthermore, erosion takes place for almost all but a line of solids of width of one to two particles, which remain in position and are significantly removed only when the flow rate is increased to a value of 80 L/min.

For the erosion tests with the thickest HEC fluid (μ =30 cp), the initial bed height were also 2.3 cm and 3.0 cm in the washouts giving a cross section for liquid flow of 0.0574 m^2 and 0.075 m^2 and thus hydraulic diameters of d_h = 3.8 cm and 5 cm respectively. Erosion occurred again from the top of the bed, with a similar erosion mechanism to that of the less viscous HEC. At a flow rate of 70 L/min, the mean velocities in the washouts regions (region B) were 0.04 m/s and 0.038 m/s respectively for the 1.5 inches and 2 inches washouts. It is evident then, that, besides the flow rate, the liquid viscosity plays a role in the erosion mechanism and results in different erosion velocities of the solid bed and this should be taken into account when modeling flow pattern transitions for solid-liquid flows. Finally, it is crystal clear that the cleaning effect of mud is higher with less viscous fluids and at high flow rates. This is seen in all Figs. 5-7.

Drill Cuttings Behaviour in Washouts

Careful observations were made of the behaviour of cuttings in the test annulus as the drilling mud was circulated. It was noticed that as the fluid moved the cuttings from the lean pipe section into the washout region, the fluid flow rate reduced significantly leading to the deposition of cuttings in the washout section.
Another feature which was evident is that the larger diameter cuttings (1 mm) settled faster in the washouts at intermediate flow rates of 70 L/min. This is opposed to the behaviour of the smaller diameter cuttings (0.1 mm); they were carried along in the fluids as it moved even at low flow rates. The bed height of cuttings in the washouts was noticed to be increasing exponentially with time though occurring mainly at intermediate flow rate of 70L/min. At high flow rates of 100 L/min, this bed height reduces significantly.

The final observation is that as the pipe inclination to the vertical was increased as shown in Figure 10, the accumulated cuttings in the washout find it difficult to entirely leave the base of the washout as indicated as point 1 and then when the cuttings leave this point at high flow rates, it bombards point 2 and falls back to point 1.The implication of this is that at high flow rates, this bombardment may cause an extension of the washout from point 2 further ahead. This would be inimical to the drilling operation. Hence high flow rates may not be desirable in washout sections as this may clean the cuttings but extend the washout.

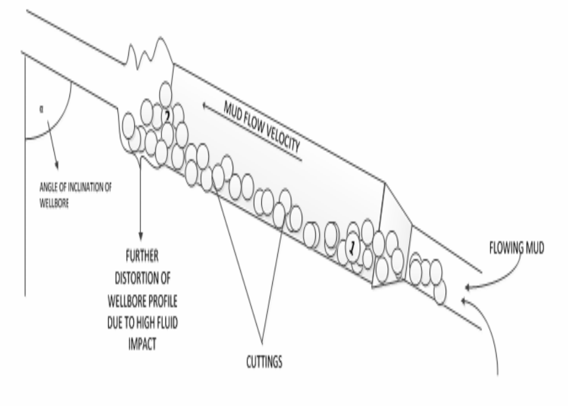

Figure 10: Effect of Turbulent Flow of mud in washout sections

CONCLUSIONS

Cuttings transport with drilling fluids in horizontal wells has been studied through a simple flow loop inclined at an angle of 8° to the horizontal. The experimental results for the erosion of solid particles by three different fluid rheologies in a pipe indicate:

- The viscosity and flow rate of the flowing fluid are the two main factors that play important role in the erosion of a solid bed.

- For the more viscous fluids (HEC) erosion starts from the top of the bed, where flow is almost turbulent, while on the front of the bed, flow is laminar for both HEC fluids. The erosion from the top of the bed is caused by the shearing action of the liquid moving above with a shear stress τ_W acting on the exposed surface area for shearing, with the impact playing a very minor role, because the exposed area of the particles is very small. Observations show that for water flow, it is impact erosion that prevails to shearing, while for the higher viscosity, HEC slurries and shearing erosion prevails.

- Cuttings removal in the washouts was easier with turbulent flow than with laminar flow and turbulent flow has the potential of extending washouts.

- For a given mud flow rate, lower cuttings bed height in the washouts is achieved as the n/k ratio increases. This means that cuttings removal is enhanced by reducing the viscosity of the fluid

- A high velocity with a less viscous fluid, resulting in high turbulence is effective in cuttings transport in washouts while, the highly viscous fluid under a turbulent flow regime easily prevents cuttings bed from sliding downward; it can lead to pack-off or cause stuck pipe of the drill string.
- An equilibrium bed height based on an optimum flow rate should be maintained in a wellbore washout so that the cuttings in such areas could serve as a fill up to maintain an equal diameter throughout the wellbore.

Symbols and Nomenclature

cm = centimeter
d_h = Hydraulic diameter
d_i = Internal diameter
d_o = Outer diameter
g = Acceleration due to gravity
H = Height of cuttings bed
HEC = Hydroxyethyl cellulose
k = Consistency Index
L/min = Litres per minute
n = Flow behaviour index, dimensionless
m = meter
mm = millimetre
m^2 = Square meter
m^3/s = cubic meter per second
N_{re} = Reynolds Number
PVC = Poly Vinyl Chloride
q = Flow rate
$Re_{(particle)}$ = Particle Reynolds number
RPM = Rotation per minute
μ = Viscosity
μ_a = Apparent viscosity
Θ = Shear rate
α = Inclination angle
ρ = Density
γ = Yield Stress
τ = Shear stress

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