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REVIEW ON HOLE CLEANING FOR HORIZONTAL WELLS

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ABSTRACT

Since the demand for oil is increasing worldwide, it is expected to drill more and more wells, like vertical, horizontal and directional wells. However nowadays the economy is a bit down, where the oil price is fluctuating. To decrease the cost of drilling operations and increase the recovery performance, the parameters that control the hole cleaning must be investigated and optimized especially in horizontal and deviated wells. In these wells the cuttings concentration is higher than in straight holes, therefore a usable hole then will be obtained. Currently the hole cleaning topic become more challenging subject matter and important issue for researchers. Therefore, in this study a set of analytical and a numerical model is presented for vertical and the horizontal well- bores. The critical transport fluid flow and the subcritical fluid flow i.e. moving upward or downward of the cutting bed concentrations is a major effect on hole cleaning. Inefficient hole cleaning and formation of beds lead to problems such as, premature bit wear, high torque and drag, stuck pipe and slow drilling rates which increase drilling time and costs. For vertical wells, as addressed in the literature, the proper hole cleaning is basically dependent on drilling hydraulics which includes; mud rheology i.e. mud properties, such as mud weight /density, viscosity, gel strength, etc. Formation of cutting beds is noticed near the entry section of the annulus and the transport of the cuttings in the annular section occurs in the form of multiphase flow regime. Drilling mud flow rate, angle of inclination and rate of penetration have a major impact on cutting concentrations. Proper prediction of these parameters is important to avoid formation of cutting beds. This research will propose a numerical model for hole cleaning in the horizontal well-bores as well as the comparison between vertical and horizontal well-bore.

Keywords: numerical study, fluid flow rate, inclination angle, yield point, plastic viscosity.

INTRODUCTION

Nowadays; the enhancement of drilling technology is a challenging topic, more specifically when it addresses the economical point of view that, horizontal drilling provides more access to the oil reservoirs, thereafter more oil will be produced compared with vertical wells.

Generally; as horizontal wellbores get longer and/or the inclination angle becomes greater, the percentage of cuttings concentration at the wellbore increases.

In horizontal segment of the wellbore, cuttings accumulate horizontally; thus, the fluid velocity has a reduced horizontal constituent. The amount/percentage of the cuttings increases with time at a specific horizontal section. Therefore, less distance will be available for the particles/cuttings to be conveyed before they travel through the buildup angle and eventually hit the borehole wall. Inefficient hole cleaning and formation of beds lead to problems such as, premature bit wear, high torque and drag, stuck pipe and slow drilling rates which increase drill time and costs.

The major parameters which affect hole cleaning in the wellbore relies on different parameters such as: drilling fluid flow rate, angle of inclination, rate of penetration, yield point, plastic viscosity, cutting size, rate of penetration (ROP), etc. Optimizing the effect of such parameters will result in maintaining the carrying capacity of the drilling fluids and ultimately enhance the design of horizontal well-bores.

[1] Investigated the settling velocity of particles, effects of flow rate, fluid viscosity and inner pipe rotation on transport mechanisms in the laboratory setup comprised of 15 feet long, 3.5-inch inner diameter vertical glass tube. [2] developed one of the first cuttings transport mechanistic. A 3D incompressible non-Newtonian drilling mud flow in a drilling model of a vertical well is considered by [3] for numerical simulations under steady flow conditions and the investigation is limited only to laminar flow at Reynolds number based on the hydraulic diameter of the annular space of Re = 1150. [4] carried out a review of cutting transport in horizontal wellbores and the advancement in cutting transportation research is summarized on turbulent flows of non-Newtonian fluids, effects of drill-pipe rotation, comprehensive solid-liquid flow model and the development of a hole cleaning monitoring system that receives all the available relevant data in real time for quick analysis and determining the borehole status. [5] implemented an inventive time dependent cutting transport model for extended reach wells. [6] developed a two-layered model for near horizontal wellbores, stationary or moving bed below a layer of heterogeneous cutting suspension, predicted thickness of the uniform bed as a function of mud flow rate, cuttings diameter, mud viscosity, pipe eccentricity and other properties of the flow.

[7] developed a three-segment hydraulic model for cuttings transport in horizontal and deviated wells. Stationary bed of cuttings in the low side of the borehole effects of drill-pipe rotation.

A simple method predicting the minimum mud pump flow rate required to lift cuttings in a deviated holes and horizontal sections is proposed by [8]. The variables required in determining the minimum flow rate are: hole diameter, angle of deviation, plastic fluid viscosity, yield point, mud weight, cutting specific gravity, and the rate of penetration. [9] used the analytical model, and the aim was to ensure the hole cleaning purpose that accounts for the horizontal or deviated wellbores. They compared their results with some of the experimental data to make sure that the model works properly. [10] used mechanistic model with aerated Newtonian fluids was developed for predicting cuttings concentrations in the annulus. Mathematical model was made and was based on the following assumptions: i) the flow is steady state and isothermal in a concentric annulus; ii) the gas phase is free of cuttings; iii) cutting particles are uniform and spherical; iv) the effect of inner pipe rotation is not considered and v) cuttings bed surface is uniform along the annulus.

[11] conducted experiments using multiphase flow loop under a wide range of air and water flow rates while introducing cuttings into the annulus with several different amounts. Data has been collected for steady state conditions, i.e. liquid, gas and cuttings injection rates are stabilized. Collection data include flow rates of liquid and gas phases, frictional pressure drop inside the test section, local pressures at different locations in the flow loop, and high speed digital images for identification of solid, liquid and gas distribution inside the wellbore.

[12] addressed a new drill pipe design integrating hydro-mechanical features in each tool joint has been developed to overcome limitations of mechanical hole cleaning devices (MCDs) in smaller diameter holes, and to extend the applications of hydro -clean drill pipe to ERD (Extended Reach Drilling) well. [13] presented a detailed combination of Larsen's model and Moore's correlation to predict and calculate the minimum flow rate for cuttings removal for all range of inclinations namely from 0° to 90°. [14] conducted several cuttings transport experiments, using a large-scale flow-loop apparatus and field measurement of annular pressure, using PWD (pressure while drilling) in a geothermal directional well recently drilled in Japan. Numerical simulation for the targeted long extended-reach geothermal well with a total depth 3,000 m, horizontal departure of 2,500 m, and maximum hole inclination angle of 70° was performed using a transient hydraulics simulator. [15] examined critical factors that affect the efficient cleaning/transport of cuttings and bit hydraulics in inclined wells with a view to understanding how to minimize drilling difficulties thereby reducing non-producing time (NPT) during drilling operations. [16] developed a new method to optimize multiple hole cleaning parameters by introducing the ant colony algorithm. The flow rate, consistency coefficient in power law model and nozzle flow area, which are three easily-adjusted parameters to control the hole cleaning on drilling site, are selected as the optimization variables. [17] explained the effect of the cuttings bed properties on hole cleaning in detail and demonstrated how the drilling operations were improved compared to earlier drilling operations using conventional drilling fluids. From drilling operations in North Sea fields, it is shown how the total drilling progress is improved. [18)] developed a transient cuttings-transport model by integrating closure laws for cuttings transport into a transient drilling model. Their model accounts for both fluid transport and drill-string mechanics and how this model was used to monitor two different drilling operations in the North Sea (one using conventional drilling and one using managed-pressure drilling (MPD)). [19] carried out flow-loop experiments to evaluate and compare sweep efficiencies of the fiber sweep [0.47% Xanthan gum (XG) and 0.04% synthetic fiber] and the base fluid (0.47% XG). Equilibrium bed heights were measured at different sweep flow rates in horizontal and inclined configurations. Viscosity was investigated together with other two influential parameters, namely fluid velocity and hole inclination under various flow conditions. It is shown that the increase in drilling fluid viscosity has improved cutting transport performance CTP by approximately 8 % at all angles provided the flow regime remained turbulent while velocity was kept constant. [20,21] described and modeled a simple and more reliable artificial neural network (ANN) for various borehole conditions using some critical parameters associated with foam velocity, foam quality, hole geometry, subsurface condition (pressure and temperature) and pipe rotation. The average absolute percent relative error (AAPE) between the experimental cuttings concentration and ANN model is less than 6%, and using MLR, AAPE is less than 9%. Learned lesson by [22] was that in a hole-cleaning situation, increasing fluid rheology moderately could lead to a reduction inequivalent circulating density (ECD). The application was also a good example of hole-cleaning monitoring. By carefully analyzing the cuttings shape and size and by comparing real-time ECD measurements with calculated ECDs, it was possible to quickly detect inefficient hole cleaning. The data from the modeling used by [23] showed that the trends in the annular hydraulics with changes in various parameters and shows also that each bore may be significantly different. The data underscores the complex interactions of the various parameters. [24] presented a new approach to achieve both optimized hole cleaning and flow rate, because of precise manipulations and redesigning of drilling mud rheological parameters, which have been elaborately explained. Calculations performed by computerized iterations via simulation software, which is developed based on theoretical concepts also addressed. An excel sheet is prepared to calculate carrying capacity index which represents an indicator for good hole cleaning in different sections.[25] implemented several collaborative drilling practices and technologies in the 12 1/4 and 8 3/8-in. vertical sections and the 8 3/8-in. curve section. In the vertical sections, ROP was increased by introducing a closed-loop vertical drilling system with motors and by optimization of bit and BHA design, which also improved run length. [26] applied the correlations and models to predict the number of cuttings and the critical velocity in the annulus, an analysis of key parameters is conducted on cuttings transport, the existing problems and characteristics of these correlations and models were summarized by [27]. Theoretical models and correlations mainly applied to calculate cuttings bed height, critical velocity to provide the guidance for the design of hydraulic parameters and the effects of flow rate, inclination, mud rheology, drill pipe

ARPN Journal of Engineering and Applied Sciences

rotation and other factors on hole cleaning, in addition, CFD simulations was applied [28].

In real time drilling, mud properties in any type of wells rather are complex with numerous parameters. However, a simplified model was created by [29] as a pre-requisite to understand these complex flow behaviors.

[30] established a physical model of carrying cuttings and borehole cleaning in wellbore of horizontal well and a critical transport mathematical model per gas-liquid-solid flow mechanism and large plane dunes particle transport theory. If the flow rate for cuttings removal is less than the optimized flow rate, the latter is selected. But if the flow rate for cuttings removal is higher than the optimized flowrate, then drilling fluid rheological properties should be changed
until the optimized flow rate becomes higher than the flow r ate for cuttings removal [31].

It was confirmed by [32] that when horizontal production wells were drilled properly, they show a significant impact on the oil recovery where it becomes double.

Optimize hole cleaning for horizontal wells: As was mentioned at the very beginning of this article, about the need for technologies to decrease the cost and improve recovery performance. One of the more significant key elements is particularly, understanding the parameters that control hole cleaning is beneficial for vertical and especially in horizontal wells. Thus, a usable hole afterwards will be obtained, therefore optimization models for vertical wells and horizontal wells will be achieved, for example the optimization for vertical wells using material balance is shown in Figure-1.

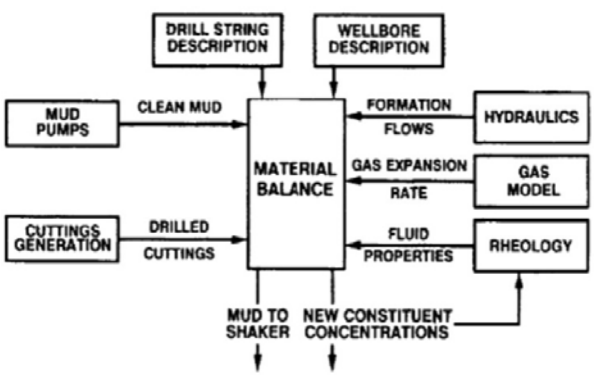

Figure-1. Material balance.

For horizontal wells, material balance expansion for horizontal segment is applied.

$$C_{VT} = C_{VM} + C_{VB} \tag{1}$$

CVT = Total Cutting Concentration
CVM = Moving Cutting Concentration
CVB = Bed Cutting Concentration

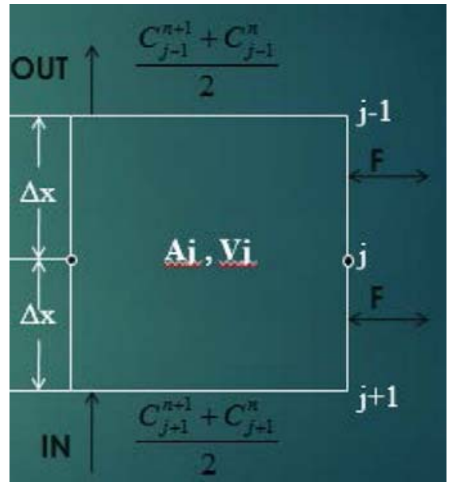

Figure-2. Hole cleaning optimization model.

$$\frac{\partial C}{\partial t} = -\frac{\partial (C\ vA)}{A\,\partial x} \pm F \tag{2}$$

The initial conditions are:
Time 0, Cutting concentration = 0 %
Mud weight = 8.45 lbm/gal, particle size = 0.25 in
Flow rate = 600/gal/min, rate of penetration = 20 ft./hr.

Where:
C = Constituent concentration
T = Time variable
X = Distance or location
ΔX = Element length
V = Constituent velocity
A = Cross sectional area
F = External flows (in/out) n = Time level number
j = Annulus Element number
i = Wellbore constituent

Equation (2) is solved numerically using the finite difference method. The solution domain is divided into 100 numbers of nodes (or elements) as shown in Figure-2. The finite difference approximation of equation (2) can be written as:

$$\left(\nu_{Dj-1} + \theta_{Dj-1}\right)C_{j-1}^{n+1} + (1-\theta)\left(\theta_{Dj+1} - \nu_{Dj+1}\right)C_{j+1}^{n+1} = \left(\theta_{Dj-1} - \nu_{Dj-1}\right)C_{j-1}^{n} + (1-\theta)C_{j}^{n} + \left(\theta_{Dj+1} + \nu_{Dj+1}\right)C_{j+1}^{n} \tag{3}$$

$$\theta_{Dj+1} = \frac{A_{j+1}}{A_{j+1} + A_{j-1}}\theta \tag{4}$$

$$\theta_{Dj-1} = \frac{A_{j-1}}{A_{j+1} + A_{j-1}}\theta \tag{5}$$

Where:

VDj = Dimensionless velocity for element j
Vj = Velocity in element j
Θ = Weighing factor

Table-1. Fluid type and slip velocities.

	Slip velocities	
Fluid	**Measured (ft/sec)**	**Calculated (ft/sec)**
Water	0.85	0.90
Low-viscosity bentonite	0.70	0.80
High-viscosity bentonite	0.35	0.40
Carpal polymer	0.45	0.45

Vertical cutting slip velocity (VCSV):

$$\nu_{Dj} = \frac{\Delta t \nu_j A_j}{\Delta x\left(A_{j+1} + 2A_j + A_{j-1}\right)} = 0.25\nu_a \quad (6)$$

In the above equation, the Formation Flow (F) was ignored.

Where Δx and Δt are the distance between the nodes and the time increment respectively. The values of Δx =element length, 50 and Δt = time step, 25 min are used in the present study. It is found that these values are small enough to generate accurate results.

Based on the importance of the parameters that affect the accumulation of the cuttings at the horizontal section, sensitivity analysis was conducted at various specific hole cleaning parameters such as fluid flow rate, angle of inclination, yield point, plastic viscosity, rate of penetration (ROP), etc. To achieve the proper investigation of cutting concentration at the horizontal section, experimental or real field data should be obtained to reach to the required objective. Table-2 shows the comparison between analytical for horizontal wellbore and the numerical modeling for a vertical wellbore, as well as Sensitivity analysis on various effective hole cleaning parameters was addressed.

RESULTS AND DISCUSSIONS

The highlight of this study is to investigate the cutting concentrations that are accumulated and hindering at the horizontal section of the wellbore where, modification of the bed cutting concentrations requires additional study. Figure-1 presents the material balance that was obtained by Iyoho, Horeth II, and Veenkant Approach. Figure-3 shows the result of the analytical model of the cuttings concentration against flowrate. The result presented in Figure-3 shows that the relationship between each other is inversely proportional, whereas the flowrate increases the cutting concentration decreases. The effects of the angle of inclination on the cuttings concentration is presented in Figure-4. It is apparent that initially the concentration of cuttings is quiet low at 20 degree, then it increases as the angle of inclination gets higher due to the near horizontal section or bedding section and the issues at the throat. Yield point is one of the more important physical property of mud, where carrying capacity must exist. Figure-5 presents the yield point performance versus cutting concentration, it is seen that the cutting concentration increases as the yield point decreases. Yield point is a kind of force to carry or lift the cuttings from the wellbore to the surface. Figure-6 shows the relationship between the cutting concentrations against the plastic viscosity, it is seen also in this plot that cutting concentration increases with an increase in the plastic viscosity, which is indirect relation to the yield point.

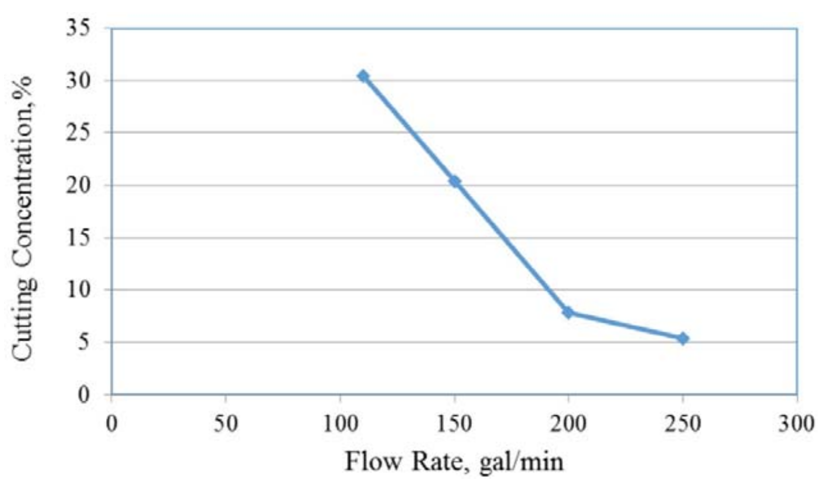

Figure-3. Analytical model - cuttings concentration vs flowrate.

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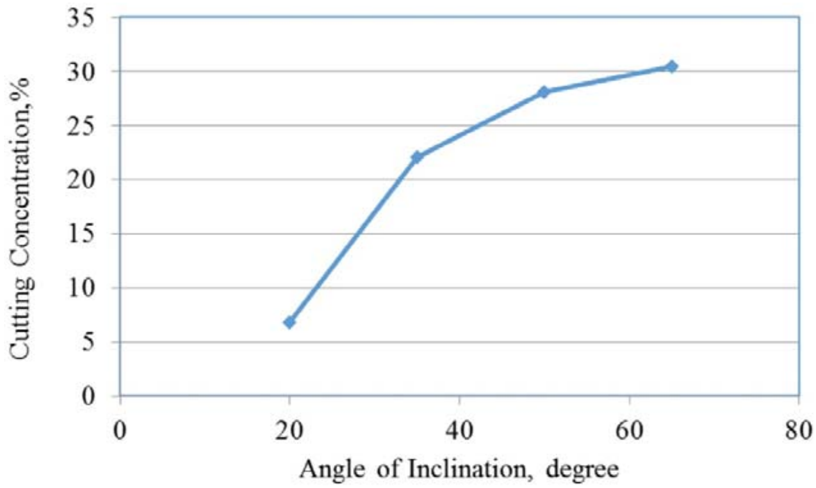

Figure-4. Analytical model - angle of inclination vs cutting concentration.

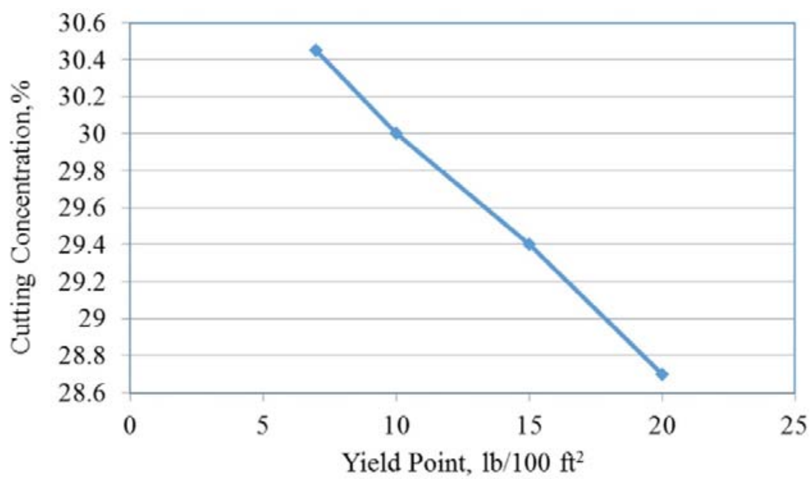

Figure-5. Analytical model - yield point vs cutting concentration.

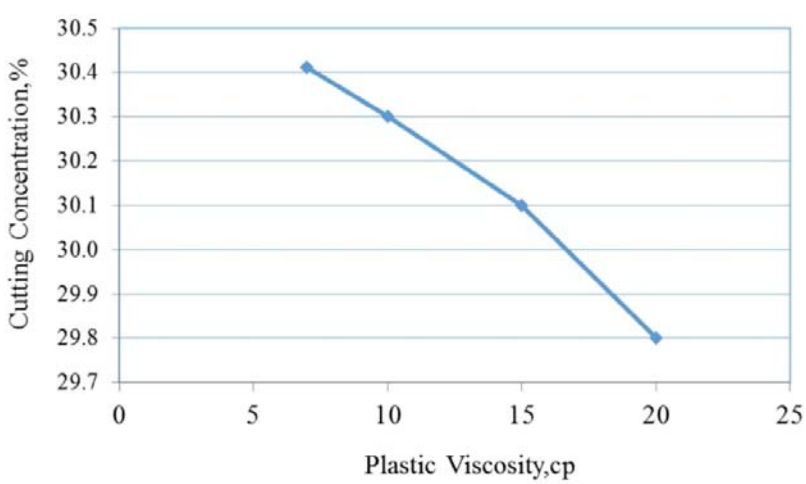

Figure-6. Analytical model - plastic viscosity vs cutting concentration.

Table-2. A comparison between numerical and analytical modelling.

Iyoho, Horeth II, and Veenkant Approach (1988)	Mirhaj, Shadizadeh and Fazaelizadeh (2007)
Hole cleaning model was assigned for vertical wellbores (material balance model)	Hole cleaning model was assigned for horizontal and deviated wellbores (material balance model), which does not depend on the location.
Parameters like wellbore constituent and individual cutting concentration were numerically calculated	An empirical model was developed, once the experimental runs were run to predict the required fluid velocity to move the cuttings, clean the hole and eventually will have a good hydraulics.
To do so the differential equation first should be solved numerically. i.e. discretize the domain into nodes or elements and discretize the differential equation to a number of algebraic equations	Mirhaj's paper was the same as Larsen, Pilehavari and Azar's paper that was on 1997 SPE drilling & completion.
After that the matrix of equations should be formed, then equations should be ready for numerical solution and finally can be solved to find the cuttings concentration at each node or element.	Experimental study was focused on the minimum transport velocity that is really needed to carry the cuttings or fractures out of the wellbores.
The cutting concentration was estimated using finite difference method.	The minimum transport velocity was calculated using an equation of: Vmin = Vcut + Vslip where; Excel sheet was prepared accounting all the Equations that are related to drilling parameters

Figure-7 presents the numerical result of the cuttings concentrations against depth at different rate of penetration. It is evident that rate of penetration increases and cutting concentration increases and it is not a depth dependent. Figure-8, which presents the trend for cutting concentration plotted against time at 15-degree inclination. After reaching a peak of 0.2160 % cutting concentration, the cutting concentration rate declines slowly to 23 minutes then becomes steady till the end. Similarly Figure-9, which presents the trend for cutting concentration plotted against time at 25-degree inclination

Figure-10 shows the numerical result for cutting concentrations against time at various angles of inclinations. It is visible that cuttings concentrations and angle of inclination increases with time. Figure-11 presents the angle of inclination against cutting concentration, it is noted that at the tangent section, where the optimum angle required for rotary drilling to best maintain both the angle and the direction is approximately 55o but this is a difficult angle at which to keep the hole cleaned. The cuttings concentrations against time and element number are shown in Figure-12 and Figure-13 and the trend shows similar results. The cutting concentration is plotted against the depth at different mud weights as shown in Figure-14. The results indicate that the behavior looks the same and the model is not dependent on the value of the mud weight, however this might be a good sign for hole cleaning. Figure-15 represents the relationship between flowrate rate and the percentage of cutting concentrations at various plastic viscosities using a numerical model. Finally, as shown in Figure-16 the relationship between the cuttings concentrations and time at different flowrates. The result shows that with an increase in time and flowrate there is a decrease in cutting concentration and that is again a good indication of the hole cleaning.

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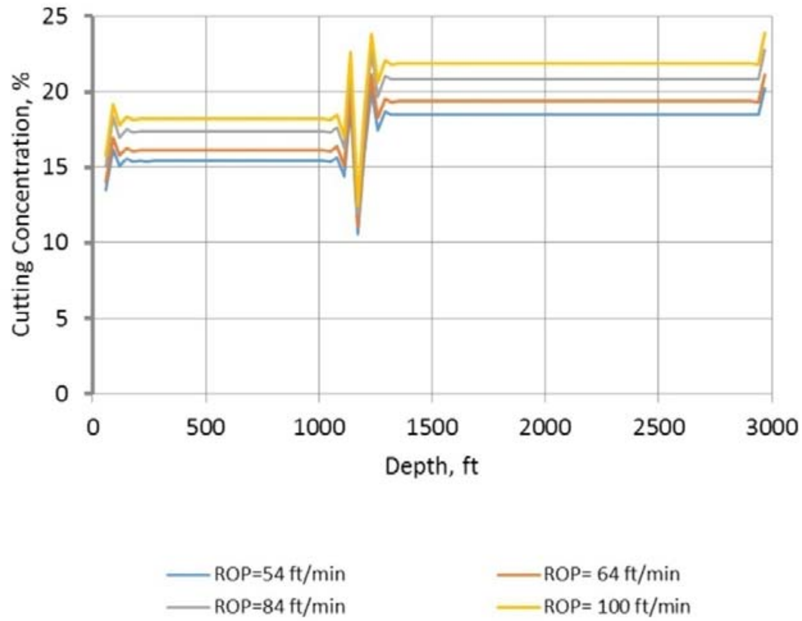

Figure-7. Numerical result - cutting concentration vs depth at various rate of penetration.

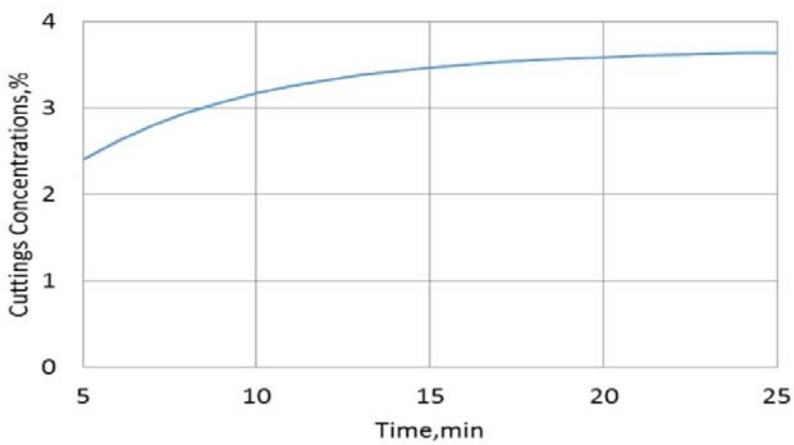

Figure-8. Numerical result - cutting concentration vs time at 15-degree inclination.

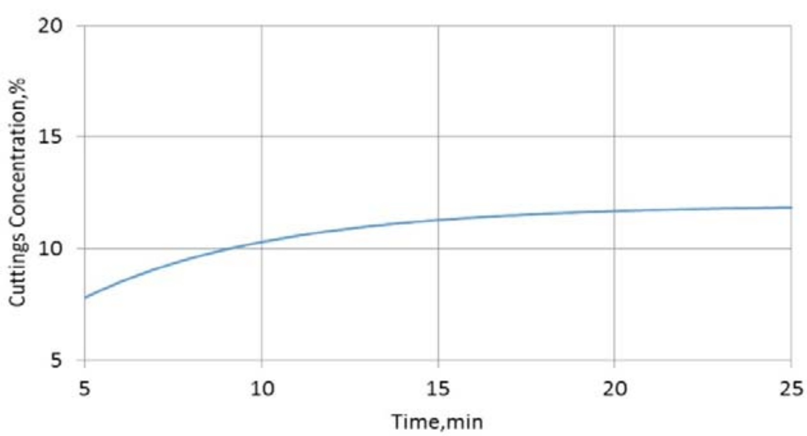

Figure-9. Numerical result - cutting concentration vs time at 25-degree inclination.

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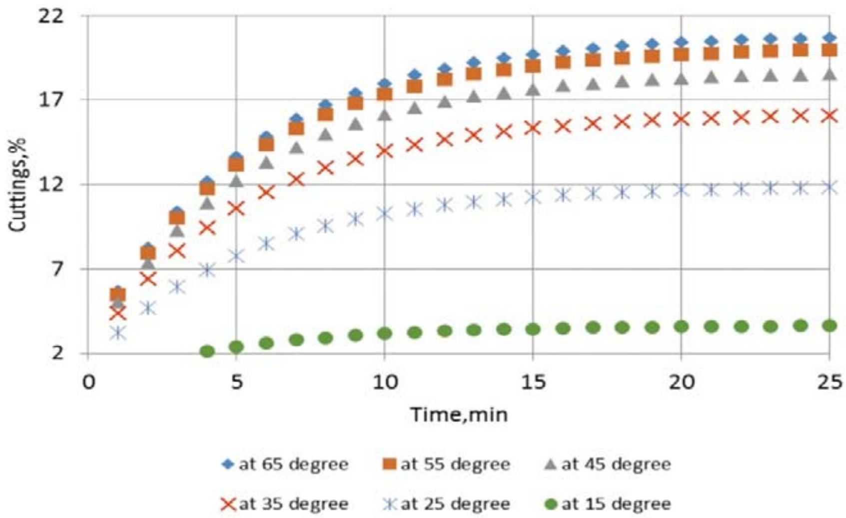

Figure-10. Numerical result-cutting concentration vs time at various angle of inclination.

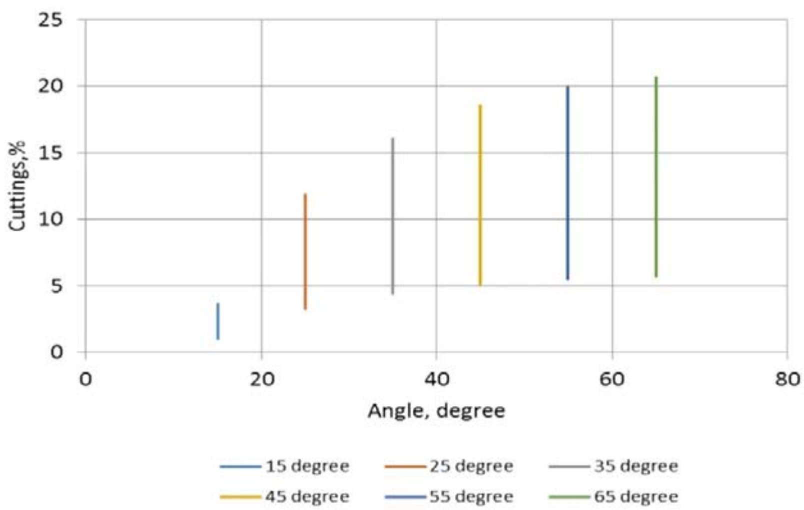

Figure-11. Numerical result - cutting concentration vs angle of inclinations.

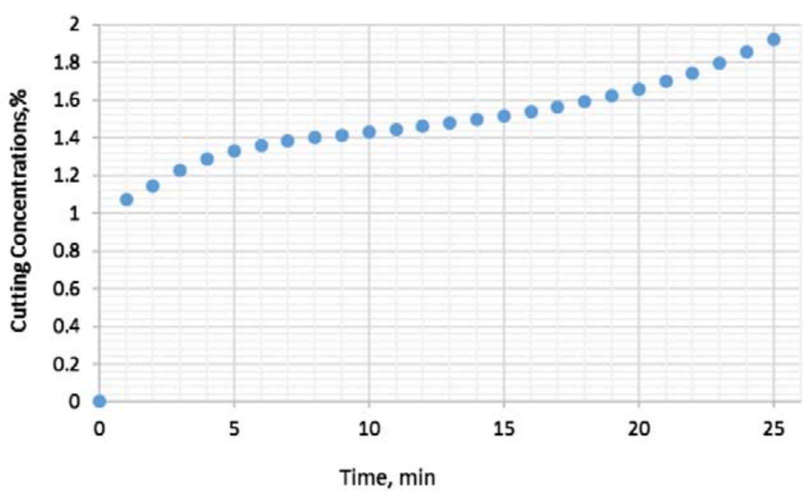

Figure-12. Numerical model - cutting concentration vs time.

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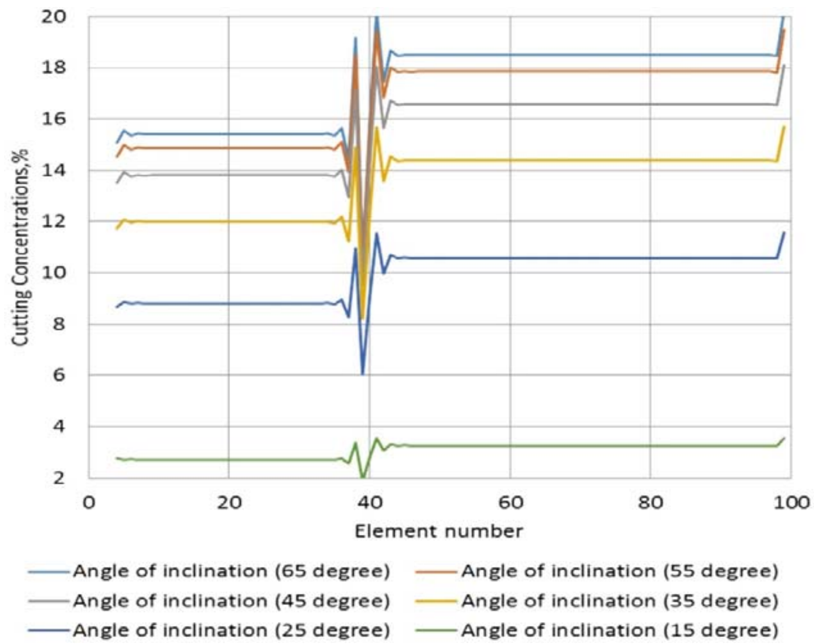

Figure-13. Numerical model - element number vs cutting concentrations.

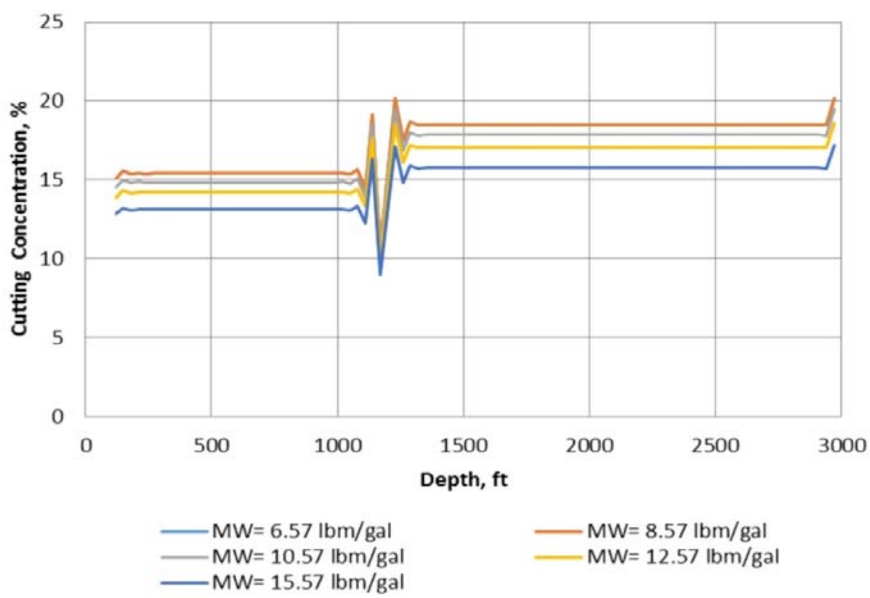

Figure-14. Numerical result-cutting concentration vs depth at different mud weights.

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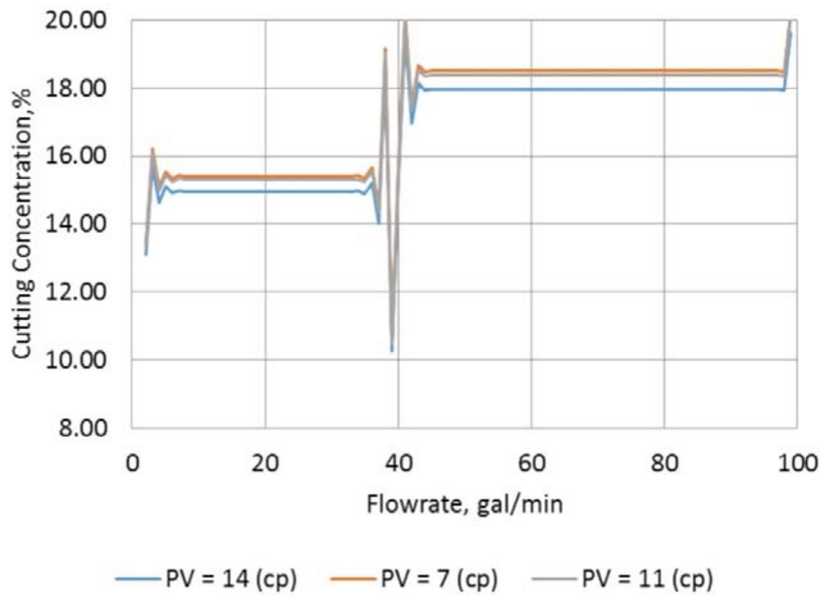

Figure-15. Numerical result - cutting concentration vs flowrate at different plastic viscosity.

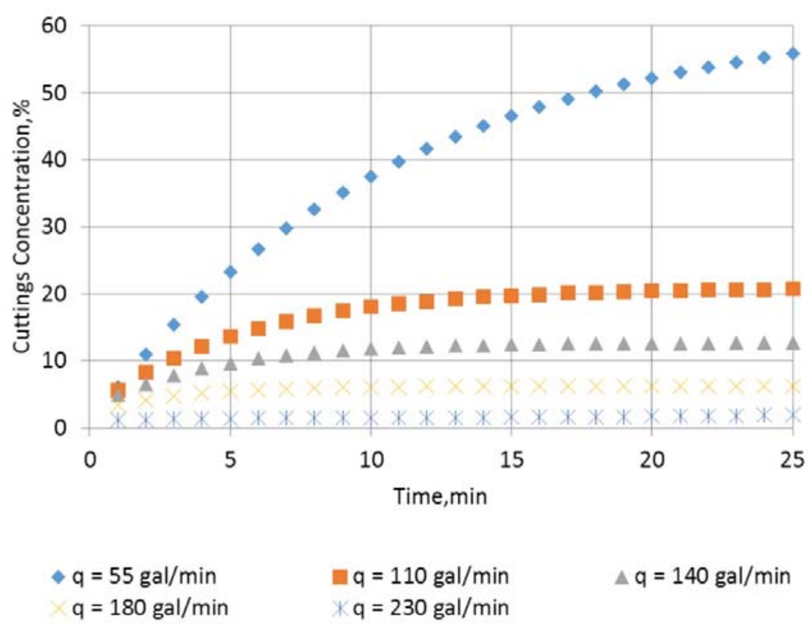

Figure-16. Numerical result - cutting concentration vs time at different flowrates.

CONCLUSIONS

The hole cleaning for horizontal and deviated wells drilling is analyzed numerically in the present article. Parametric study is carried out to understand the effect of each parameter on the cutting concentration with time of the directional drilling. The following parameters are considered in the present study: flowrate, angle of inclination, yield point, plastic viscosity and depth of the well. The unsteady cutting transport model is employed in the present analysis. The finite difference technique was assigned to solve the cutting transport equation numerically for the horizontal wellbore to obtain the cutting concentrations. The effects of the parameters can be summarized as follows:

As ROP increases the cutting concentration increases too. Also, numerical results show that at higher flow rates cutting concentration decreases.

At the same depth for numerical results, as ROP increases cuttings concentrations increases.

Cuttings concentration decreases with an increase in the flow rate of the drilling mud.

Cuttings concentration decreases with an increase in time. Also as the number of element increases the cuttings increases too.

The present model can be extended to include the bed cutting concentration with the effect of other parameters, such as three-dimensional modelling, pressure of the drilling mud, drilling string rotation among others which need more and more investigations.

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