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MASTER'S THESIS

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Cutting transport models and parametric studies in vertical and deviated wells

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Abstract

Field experience shows that the accumulation of cutting in a wellbore causes several drilling problems. These include an increase in torque and drag, which may limit drilling from reaching to a desired target formation. In addition, it may cause drill string sticking and poor hydraulics as well. Therefore, an efficient hole cleaning is the most important aspect of drilling operation.

Hole-cleaning is a very complex subject, which integrates fluid mechanics, fluid rheology, thermodynamics and mechanics. Since the introduction of hole-cleaning research several works have been carried out to investigate the behavior of cutting transport through modeling and experimental studies.

In this thesis, the sensitivity of several parameters associated with the hole-cleaning was studied. For the analysis, widely known industry standard software, WellPlan^{TM} /Landmark, was used. The results are in line with experimental works documented in literatures. The overall simulation analyses are summarized. In addition, list of recommendations as future work are proposed.

Contents

Acknowledgements

I would like to express my deep gratitude to Mesfin Belayneh for his invaluable advice and consistent guidance throughout this study. Secondly, I want extend my gratefulness to my wife and children for their continuous support and encouragement during my studies. Finally, I want to thank God for cherishing me with his love and kindness.

1 Introduction

This thesis analyzes the sensitivity of cutting transport phenomenon with respect to various parameters using WellPlan^{TM} software [3]. Landmark's WellPlan™ software is widely used in the oil industry. 11003ft length real wellbore was considered for the simulation study.

1.1 Background

Circulation of drilling fluid is an integral part of the drilling operation. Figure 1.1 illustrates a typical rotary drilling system [1]. The drill bit crushes the rock formation into small pieces called cuttings. The drilling fluid is pumped through pipe and then circulated back through the annulus bringing cuttings to the surface facilities such as shale shaker and mud pits [2].

The ability of circulating drilling fluid system to transport cuttings is known as the carrying capacity of the drilling fluid. The term carrying capacity is also called hole-cleaning capacity. The carrying capacity is basically a function several parameters mentioned in Table 1.1. In this thesis work, the effect of these parameters on the hole-cleaning phenomenon will be evaluated. Before drilling, the common practice during planning phase is to perform a simulation study in order to predict effective cleaning efficiency of a given mud system with respect to the operational parameters and cutting properties. The prediction is performed by calculating the critical cutting transport velocity. The critical transport fluid velocity is defined as minimum fluid velocity required preventing cutting bed formation and allows cuttings upward transport [3]

Hence during planning phase, proper design and implementation of cutting transport is very important for the success of the overall drilling operation. Poor hole-cleaning leads to several negative effects. The overall effect is extending drilling time and increasing drilling cost. Some of the consequences related to poor hole-cleaning are [4]:

- Slow rate of penetration,
- Increase drilling string torque (increase in rotary power requirement),
- High drag (in ability to reach target),
- Risk of pipe sticking (fishing or loss of hole),
- Difficultly in casing landing due to drag and cutting accumulations,
- Challenging problems during cementing (reason for channeling),
- Difficulty in logging

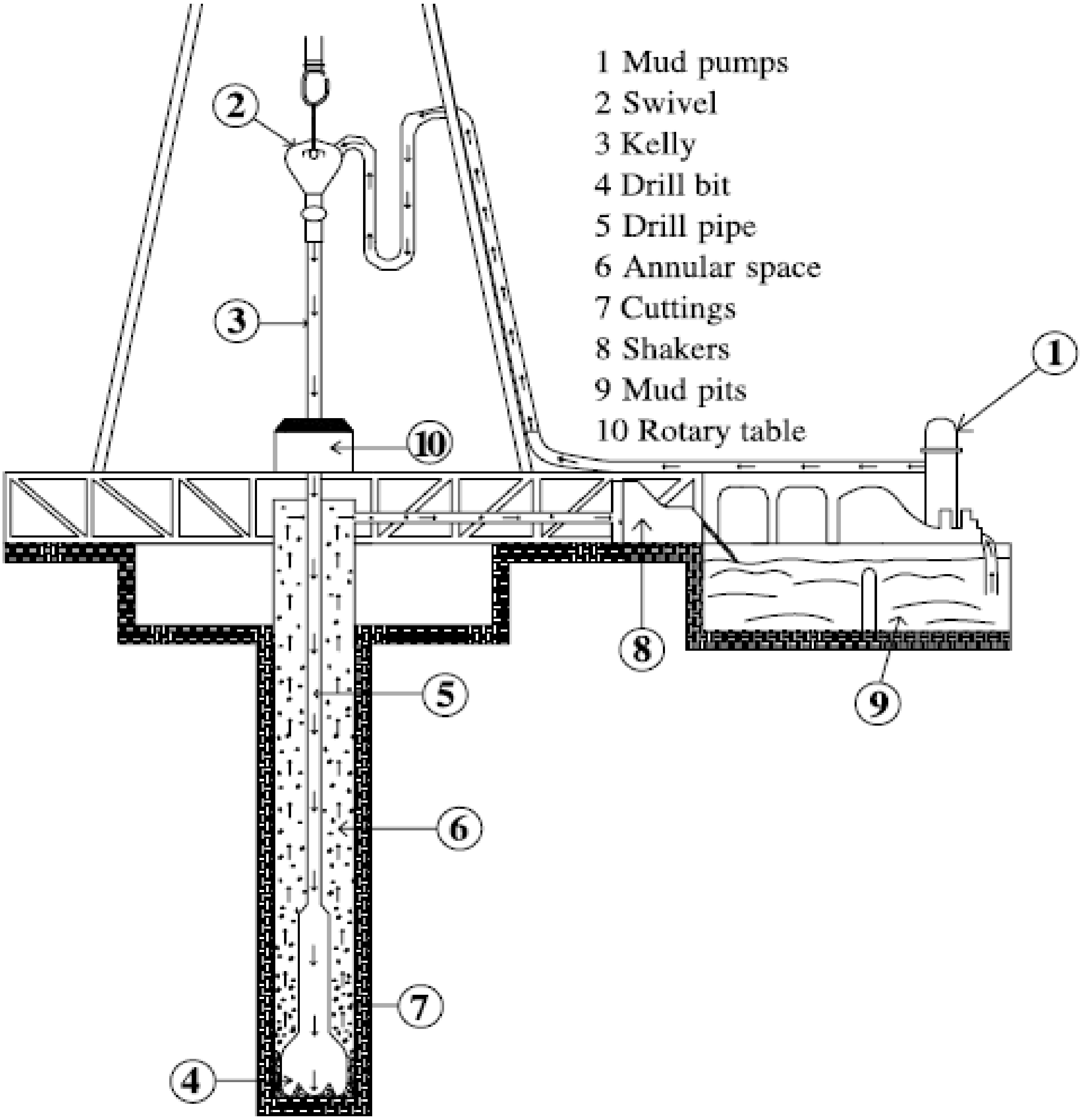


Figure 1.1: Drilling system [1]

Poor hole cleaning problems is common in directional and horizontal drilling as illustrated in Figure 1.2. Cutting bedding development occurs as angle increase from vertical to horizontal provided that the flow rate is not sufficient for cleaning. In addition during a sudden pump shut down, or during connection cutting bed would slide down in intermediate angles between about 40-55/60 deg. Figure 1.2 illustrates cutting deposition and drill string sticking during tripping operation [35].

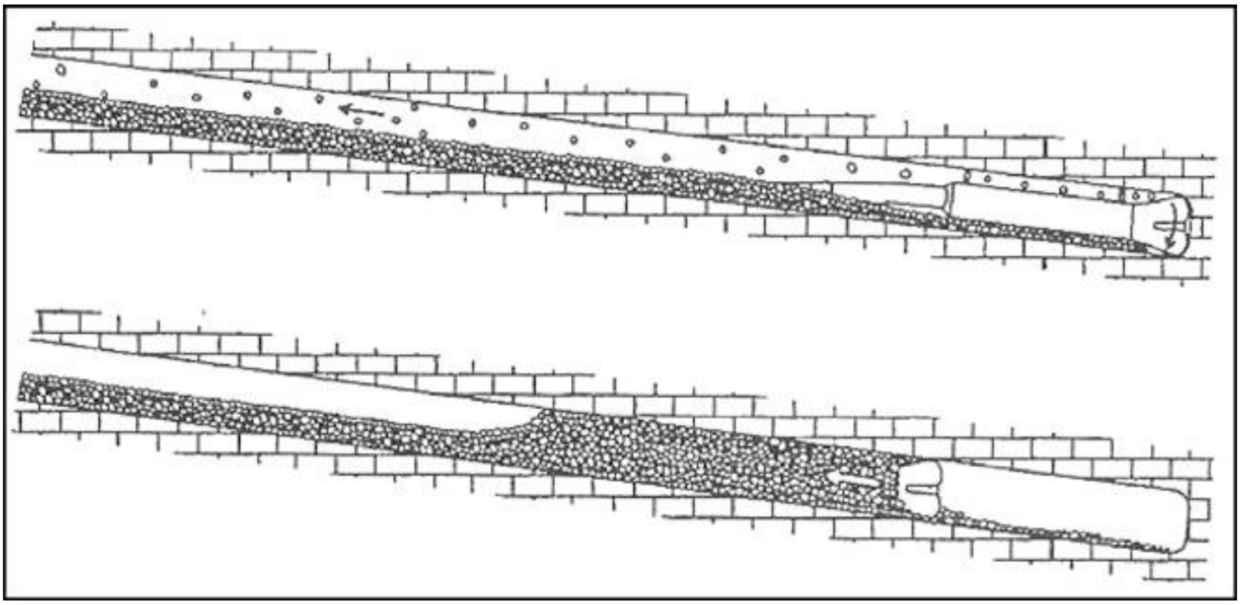


Figure 1.2 Illustration of cutting bed deposition in deviated well [35]

Transportation of cuttings in the annulus is a very complex process. It is affected by many parameters. Several investigators [5] [6] [7] [9-22] have listed the most relevant factors that affect the carrying capacity of drilling fluids. As shown in Table 1.1, the parameters can be categorized into three groups: Fluid parameters, cutting parameters and operational parameters:

Fluid parameters	Cutting parameters	Wellbore configuration + Operational parameters
Mud density	Cutting density	Angle of inclination
Rheology	Cutting size	Pipe rotation
	Shape	Rate of penetration
	Cutting concentration	Eccentricity of the hole
	Bed porosity	Flow rate
	Angle of repose	Depth
		Hole size/Casing well inside diameter

Table 1.1: Parameters that influences hole-cleaning

Laboratory test results show that relatively a higher flow rate can remove cuttings for any fluid, hole-size, and hole-inclination angle. However, the higher fluid flow rate will also increase the equivalent circulation density of the mud system. This as a result may cause well fracturing. To avoid this minimization of pressure losses in the annulus is an important issue for drilling in an extended reach well. The pressure losses depend on the fluid velocity, fluid density, and particle concentration. Therefore, a compromise between well stability and cutting transport should always exist, which one can optimize an appropriate flow rate for these operations.

Efficient transportation of cuttings is an important factor for a good drilling operation. Using WellPalan^{TM} software, this thesis will analyses the sensitivity parameters on cutting transport in a vertical and an inclined well geometry.

1.2 Problem formulation/Problem statement

Since the introduction of hole-cleaning research several studies have been documented. The studies include both experimental and modeling works, which investigated different mechanisms under different operational and fluid/cutting parameters that governs cutting transport.

From the Larsen's [5] experimental data (Figure 1.3), one can observe different cutting transport phenomenon as a function of well inclination. However, the Larsen model handles only from the 55-90deg well inclination. The Chen's [6] and Moore's [7] models handle only for vertical well. Rubiandini [8] developed a method of correlation which is a linear interpolation between the vertical and 45deg. However, the experimental data of Larsen doesn't show the linear trend between vertical and 55deg.

Recently an extensive literature review on cuttings transport is published by Nazari et al [4]. The paper summarizes the effect of drilling parameters on cuttings transport in deviated and horizontal wells.

However, this thesis will look into the sensitivity of these effects under various drilling operation and fluid properties.

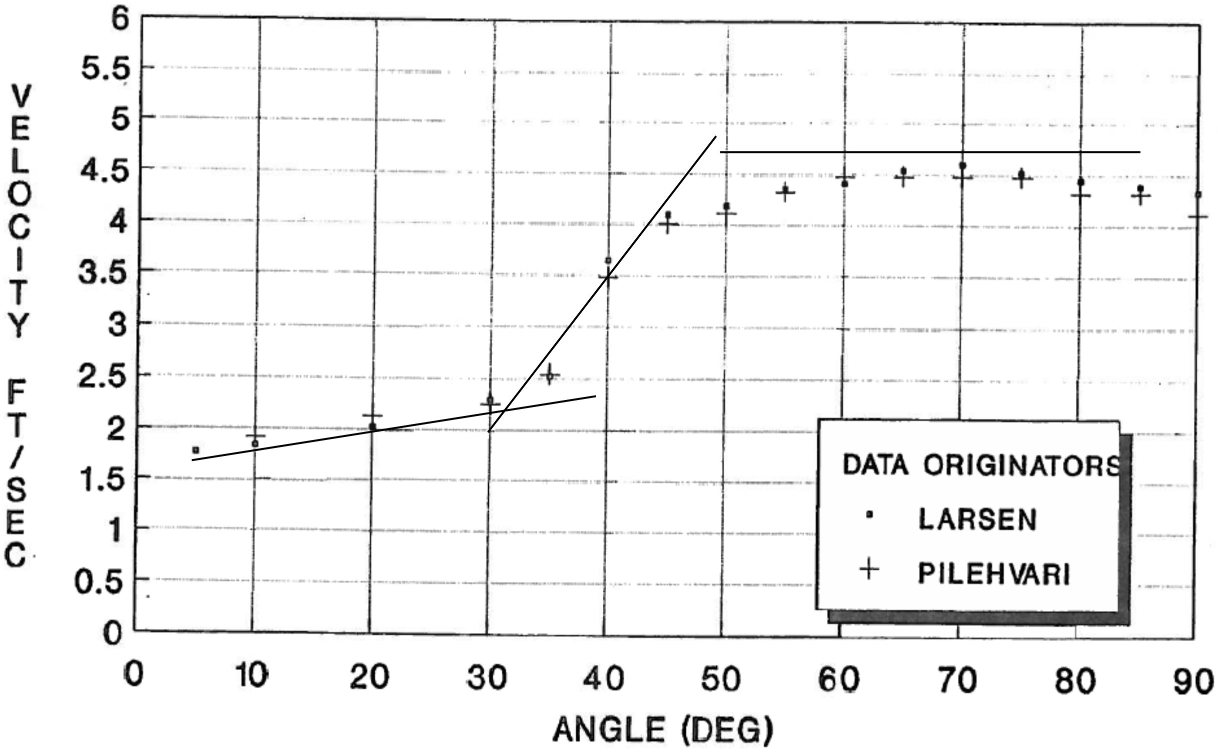


Figure 1.3: Laboratory observer transport velocity [5]

Some of the hole-cleaning issues that this thesis is trying to look at are:

- What is the combined effect of operational parameters and drilling fluid properties?
- What is the combined effect of operational parameters and cutting properties?
- Does the application software describe the major phenomenon observed in laboratory experimental measured data?
- What is the effect of rheology model on cutting transport simulation?
- What is the effect of well length and size on cutting transport?

1.3 Objectives

The primary objective of the thesis is to perform a simulation study to investigate the impact of various parameters on cutting transport. The activities are to:

- ✓ Review different cutting transport models, experimental laboratory investigations and their model verifications

- ✓ Simulate the impact of various parameters on cutting transport in vertical and deviated wells using WELLPLAN^{TM} Landmark software.
  - ○ The parameters to be used for sensitivity parametric simulation studies are various operational, wellbore configuration **(**well size & inclination), drilling fluid and cutting properties listed in Table 1.1.
  - ○ During simulation a single and combined effect of the parameters on cutting transport will be investigated.

- ✓ Compare the simulation results with the trends of experimental observations documented in the reviewed literatures.

2 Literature study of cutting transport

As mentioned earlier, in literature there are several studies documented on cuttings transport issues. These include i) empirical and ii) theoretical (mechanistic model) and iii) experimental works.

- Empirical correlations studies presented by references [6] [7] [32] [33] [34]
- Mechanistic modeling presented by references [20] [23] [35]
- Experimental works under small and large scale flow loops performed by references [5] [6] [7] [9-22] [32-36].

The cuttings transport behavior in deviated well is different from in vertical well. The problem become worst in deviated well.

This section highlights the major investigation documents in literature.

2.1 Experimental

This section briefly highlights the experimental works with regards to the experimental set up and the major investigations.

Tomren et al. (1986) [9] reported the results of laboratory experiments carried out with various drilling fluids and cuttings in plastic pipes at well inclination angles varying from vertical (0) to horizontal (90°). The length of the test section was 40-ft. The annular size of 5 in x 1.9 in. and flow rates up to 200 gal/min. The pipe rotates in the annulus. The investigators observed that:

- For near vertical well (i.e. when deviation from vertical is less than 10°), cuttings transport is similar to the vertical situation; It was observed that with 10° tests, cuttings movement and concentrations are only slightly worse than with vertical tests.
- When well inclination increases, a cuttings accumulated and hence bed develops at low flow rates;
- For a given flow rate, the bed thickness increases with deviation up to an angle where it becomes independent of the deviation angle;

- In given conditions of deviation and flow rate, the bed thickness is strongly influenced by drillpipe eccentricity, but only moderately influenced by fluid viscosity. The transport performance reduces as the well inclination and rate of penetration increase.
- Hole-angles of 40 to 50° are critical because of cuttings buildup and downward sliding of the bed of cuttings.
- High-viscosity muds were observed to provide better transport than low-viscosity muds.

Ali Piroozian et al 2012 [10] have experimentally investigated the influence of the drilling fluid viscosity, velocity and hole inclination on cuttings transport in horizontal and highly deviated wells. For the investigation, the authors have considered three types of drilling fluid. The experiment was conducted using a 17-feet long flow loop of 2-in. diameter as the test section. During testing, they have determined the amount of cuttings transport performance (CTP) from weight measurements. The result of the experiment shows that:

- For constant flow velocity, increase drilling fluid viscosity has improved CTP by approximately 8 % at all angles provided the flow regime remained turbulent
- Further increase of viscosity as flow regime was turning into transient or laminar flow, has reduced CTP by a total average of 12 %.

Cutting transport is becoming difficult in inclined and horizontal wells. This is because the gravitational force causes the particles settle down to the bottom Mengjiao et al [11] have written a new approach to improve cutting transport in an extended reaches horizontal wells. The method is to counteract the gravitational force while simultaneously increasing the drag force by attaching the drilling particles with chemical surfactants as illustrated in Figure 2.1.

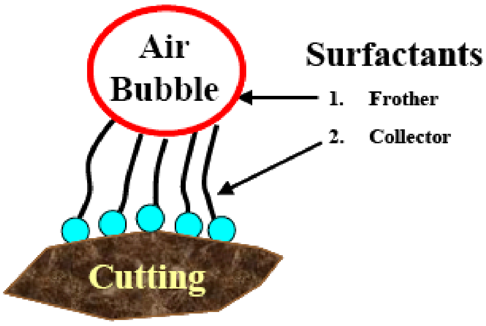


Figure 2.1: Diagram of Air Bubble attached to cutting particle [11]

During the lab-scale test, the performed cutting transport experiments with and without chemical additives. Their test result in horizontal section shows that:

- Without chemical additives, no cuttings were transported
- With the addition of straight chained chemical surfactants, 30% of the cuttings were carried out by air and many others were carried partially across the tube
- Use of branched chemical surfactants, 58% of the cutting were transported

Ford et al 1990 [12] have experimentally investigated the cutting transport phenomenon in an included wellbore. The main investigation obtained from the experiments is that the velocity that initiates cuttings transport is sensitive to hole-inclination. The effectiveness of a circulating fluid in removing drilled cuttings dependent on the rheology of the fluid and the fluid flow pattern (ie. laminar or turbulent). Observation in water shows that under turbulent flow the cutting transport was very effective. Operational parameter such as pipe rotation shows little or no effect when circulating with water but it significantly reduced the critical fluid transport velocity when circulating with medium or highly viscous fluids.

Hareland et al (1993) [13] have experimentally investigated the limestone cutting transport behavior in Low-Toxicity Invert Emulsion Mineral-Oil-Based and Water-Based Muds systems. As reported by the authors, their experimental set up similar other investigators such as Tomren et al [9] and Okanji’s [14] work. Analyzing the observed experimental data, the authors came to the following conclusion:

- Except the vertical or near vertical well inclination, at all angles it was observed that an increased yield point and plastic viscosity of both mud systems results in decreased cuttings transport rate. They have also observed that this effect is more severe in the inverted emulsion oil-base muds.
- At higher well inclination, decreased yield point and plastic viscosity, coupled with increased flow, shows improve hole-cleaning for both mud types. This conclusion is based on the experimentally observed bed sliding and film formation.
- For a well inclination from 40° to 50°, water-base muds show a better hole cleaning than mineral oil-base muds provided similar rheology.

Okrajni, and Azar 1985 [14] have experimentally investigated the effect of mud rheology on annular hole-cleaning. From the study, they have identified three cutting transport regions namely;

- Region 1 (0 to 45°),
- Region 2 (45 to 55°) and
- Region 3 (55 to 90°).

Their work shows that under turbulent regime, the cuttings transport is not affected by the mud rheological properties (yield and YP/PV ratio) in all three regions. On the other hand when the flow is laminar, higher mud yield value reduces cuttings concentrations, which shows a better transport performance. The effect of mud yield value is very significant in the range of low-angle wells (Region 1) and becomes nearly negligible in Region 3. The authors also observed a poor cleaning (i.e. highest annular cuttings concentration) when the angle was 40 to 45 ° range. This observation was when low flow rates were used. They also analyzed the effect of eccentricity and the result shows that a relatively small effect for low-angle inclination (Regions 1 and 2) for any flow regimes. The effect becomes moderate in Region 3 under turbulent flow and significant for laminar flow. They also observed in general that the mud flow rate has a dominant effect on annular hole-cleaning.

SIHerman, and Becker**,** 1992 [15] performed a full scale based hole cleaning experiments in an inclined well varying from 45-90deg. The length of the experimental was 18.3 m long. The drill pipe 3- and 4.5-in. and the wellbore was an 8-in ID diameter.

The investigators evaluated the effect of several parameters on hole-cleaning. The parameters are mud velocity, mud density, mud rheology, mud type, cuttings size, rate of penetration (ROP), drillpipe rotary speed, drillpipe eccentricity, drillpipe diameter, and hole angle. Mud velocity and mud density have the greatest effect on hole-cleaning. According to the investigators, as the mud weight increases the cutting beds shows decreasing. The drillpipe rotation effect on cutting buildup is greater under certain conditions such as at inclination angles near horizontal, for small cuttings (0.08 in. [2 mm]), and low ROP (50 ft/hr). They have also reported that bed Beds forming at inclination angles between 45 and 60° may slide continually and tumble down. At angles from 60 to 90° from vertical, cuttings beds are showing little sliding or reducing tendency.

Hussain et al 1983 [16] have conducted an experimental study of cutting transport. Their investigation shows that annular velocity and yield strength of drilling fluid increases are favorable conditions for efficient hole-cleaning.

Sifferman et al. 1974 [17] conducted experiments using a full scale vertical annulus to study the various parameters affecting cuttings transport ratio to annular velocity for different systems of field mud. They concluded that rotary speed, feed concentration, annular size and pipe eccentricity had minimal effect on cutting transport.

A large scale experimental study was performed using several drill pipes and casing sizes in 140ft vertical flow system. The annular velocity used for the evaluation was varied (4 to 200 ft/min), using different fluid rheological properties, cutting sizes, and operational parameters. Among others observations; the most important controlling factors are:

- Annular velocity and rheological properties are the most cutting transport controlling parameters. The annular velocities of 50 ft/min provided sufficient cutting transport in typical muds.
- As the fluid viscosity increase the cutting transport efficiency of the fluid increase. In laminar flow of oils as transport fluid, cutting transport is 85 to 90% of the theoretical values based on the terminal slip velocity of the cuttings. In turbulent flow, cutting transport is around 75% of the theoretical values.
- Casing size and drilling fluid density shows a moderate effect. But the drill pipe rotation, drilling rate (cutting feed concentration), and drill pipe eccentricity had a minimal effect on cutting transport.

2.2 Experimental and modeling

This section also presents the some of the experimental works along with model verifications. Modeling is an important part of hole-cleaning research. If the model predicts the cutting transport phenomenon one can run several computer experiments. In this thesis work several simulation works will carried out.

Gavignet and Sobey (1989) [18] presented a cuttings transport model based on physical phenomena, is known as the double-layer model. The investigators have compared their model against Iyoho et al's laboratory data. The model shows relatively good prediction of Carbopol fluid system than the water.

Paden et al. (1990) [19] have developed minimum transport velocity prediction models for: a) cuttings suspension and b) cuttings rolling. The predictions were compared with laboratory data. The investigators observed than as increase in the viscosity of the circulating fluid results a decrease of MTV. The effectiveness of hole-cleaning is dependent on the rheology of the fluid and fluid flow regimes (i.e laminar or turbulent flow).

Clark and Bickham (1994) [20] developed a mechanistic model is based on the momentum-forces acting on a particle. The model predicts the minimum pump rate to transport a particle. They define three modes for cuttings transport: settling, lifting, and rolling each dominant within a certain range of wellbore angles. The authors came up with solutions for the minimum velocities to transport particle on the bed. However, the model takes into account the annular (axial) velocity only without consideration of drill string rotational speed. The model predicts quite well the given experimental data.

Duan et al. (2009) [21] experimentally investigated the cutting transport phenomenon of smaller sized cuttings. They have studied two conditions for efficient transport. These are 1) the minimum fluid velocity required to initiate solids-bed erosion, 2) the minimum fluid velocity that prevent bed formation. For the investigation, they used a full scale flow loop (8 × 4.5 in., 100 ft long) in water and polymer fluids and hole-inclinations. The cuttings used were 0.45-mm and 1.4-mm sands

The results show that in terms of bed erosion water is more effective than low-concentration polymer solutions. Their experimental observation also shows that polymer solutions prevent bed formation better than water. The authors also developed a mechanistic model for sold bed and showed the model predictions in good agreement with experimental results. In addition, the authors recommend that water or low viscous fluids are preferable to high viscous fluids for cleaning out operations when drilling is stopped. They also recommended that polymer solutions be used for small-solid transport when drilling is in progress.

Zeidler [22] conducted a series of experiments in an attempt to predict recovery fractions. The investigator developed a correlation for settling Velocity of cuttings in a Newtonian fluid end for the recovery fraction of cutting subjected to turbulent flow of water in the annulus. He concluded that pipe rotation had a significant increase in the recovery of particles, while viscosity is not a major factor in the transportation of cuttings.

2.3 Modeling without experiment

A more advanced three layer mechanistic model has been derived by Nguyen and Rahman (1998) [23]. However, the applicability of the model was not verified against measured data. The authors have presented a parametric study to investigate the effects of cutting, drilling fluid, and eccentricity parameters on cutting transport phenomenon,

However, the authors have indirectly verified their simulation results against the experimental data trends reported by several investigators, which are listed in the paper.

3 Theory related to cutting transport

3.1 Fluid rheology

The fluid rheology models are used in cutting transport simulator (Wellplan^{TM}, [3]). This section therefore reviews the models. During simulation, the choice of rheology model on cutting transport will be analyzed in simulation part of the thesis (Section §4.4.3.2, page 41).

Fluid categorized as Newtonian and non-Newtonian. The non-Newtonian rheological models include Bingham plastic, Power law, API, Herschel-Bulkley, Unified, and Robertson-Stiff. A typical rheological behavior of the fluid systems is shown Figure 3.1.

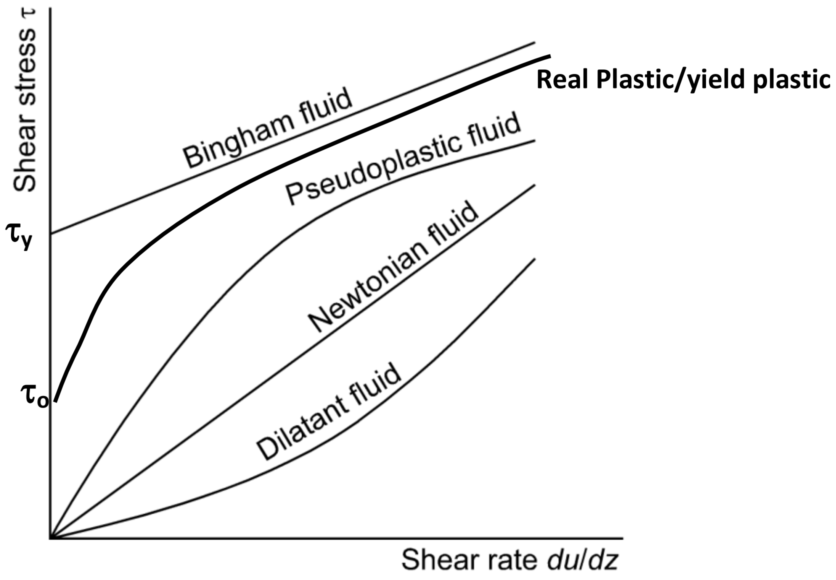


Figure 3.1: Illustration of fluid rheology behaviours

3.1.1 Newtonian Model

A fluid that has a constant viscosity at all shear rates at a constant temperature and pressure is called a Newtonian fluid. An equation describing a Newtonian fluid is given below [24]:

$$\tau = \mu\gamma \tag{1}$$

When the shear stress (τ) of a Newtonian fluid is plotted against the shear rate (γ) in linear coordinates a straight line through the origin results. The Newtonian viscosity (μ) is the slope of this line.

3.1.2 Bingham Plastic Model

The shear stress -shear rate is a linear relationship and slope represents the Bingham plastic. The intercept is the yield stress of the fluid. To initiate flow, a minimum pressure is required to overcome the yield stress. The model is given as [24]

$$\tau = \mu_p\gamma + \tau_y \tag{2}$$

The yield point/yield stress (τ_y) and plastic viscosity (μ_p) can be calculated by the following equations:

$$\mu_p\,(cP) = R_{600} - R_{300} \tag{3}$$

$$\tau_y\,(\text{lbf/100sqft}) = R_{300} - \mu_p \tag{4}$$

3.1.3 Power Law Model

This model is used to better representation of the behavior of a drilling fluid since the viscosity is the shear rate dependent. As shear rate increases most of drilling fluid shows a shear thinning behavior. The model is given as [24]

$$\tau = k\gamma^n \tag{5a}$$

The parameter *k* represents the consistence index and *n* is flow behavior index. These parameters can be calculated from the measured rheometer data.

$$n = 3.32\log\left(\frac{R_{600}}{R_{300}}\right) \tag{5b}$$

$$k = 510\left(\frac{R_{600}}{511^n}\right) \tag{5c}$$

Where, *n is dimensionless* and *k* is given by $lbf/100ft^2$

3.1.4 Herschel-Buckley

Unlike the power law model, the Herschel-Buckley model assumes that drilling fluid has a certain yield stress. Therefore, this model is the modified version of power law model. The model is given as [25]

$$\tau = \tau_o + k\gamma^n \tag{7}$$

The parameter τ_o is calculated from the following equation.

$$\tau_o = \frac{\tau^{*2} - \tau_{\min} x \tau_{\max}}{2x\tau^* - \tau_{\min} - \tau_{\max}} \tag{8}$$

The parameter τ^* calculated by interpolation, which corresponds to γ^*:

$$\gamma^* = \sqrt{\gamma_{\min} x \gamma_{\max}} \tag{9}$$

From Eq. 10, $\gamma^* = 72.25 \text{ sec}^{-1}$.

3.2. Basic physics related to cutting transport

From mechanics point of view, the transport, deposition or suspension mechanism of cutting is determined by the forces acting on a particle as illustrated in Figure 3.2. As cutting transported through the annulus, it experiences several types of loading. These are to mention in general categorized as hydrodynamic forces static forces, and colloidal forces. In addition sticking force due to the stagnation of the mud system. According to Duan et al. (2009) [21], the cutting loading forces are:

1. Gravity, F_g, and buoyancy, F_b, are static forces which are due to the properties of the particle and its surrounding fluid only and do not depend on the fluid flow.
2. Drag, F_d, and lift, F_L, are hydrodynamic forces incurred by the fluid flow.
3. Van der Waals dispersion, F_{van} forces are colloidal forces existing between any neighboring particles.

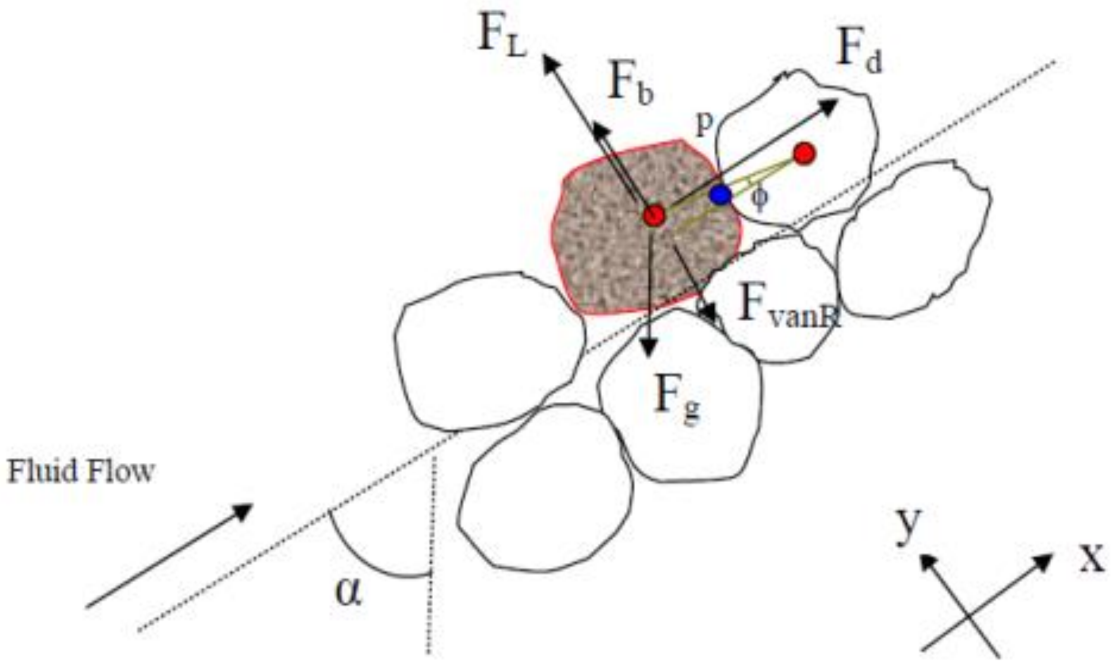


Figure 3.2: Forces acting on a single cutting particle on the surface of a cutting bed [21]

Figure 3.3a shows an illustration of cutting in suspension and cutting deposition. Figure 3.3b also illustrates the action of forces on cutting particles and the action of pie rotation on altering the velocity distribution [26]

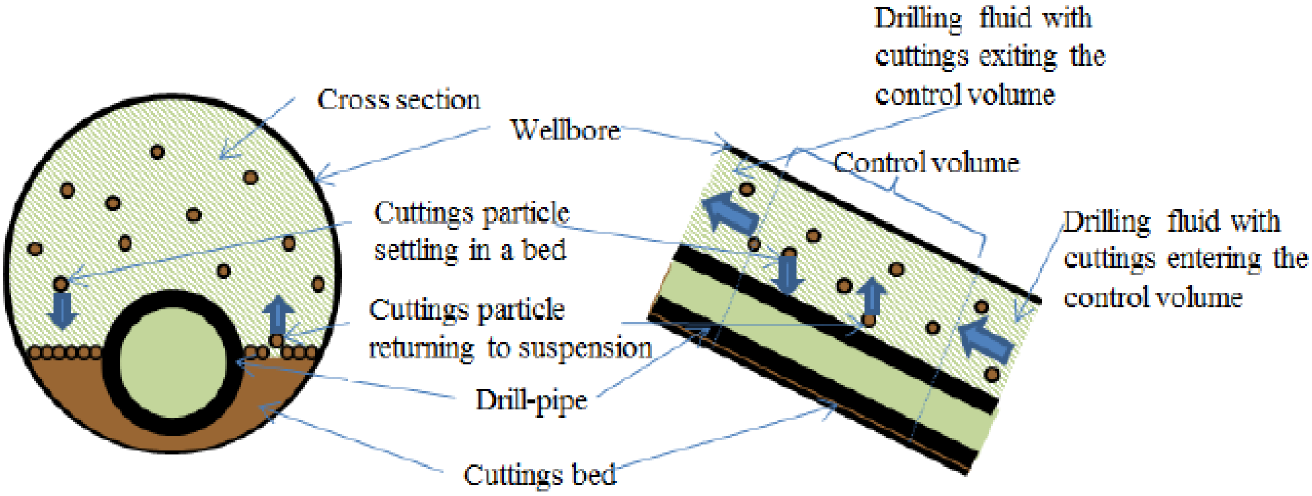


Figure 3.3a: Cutting in suspension and cutting deposition [26]

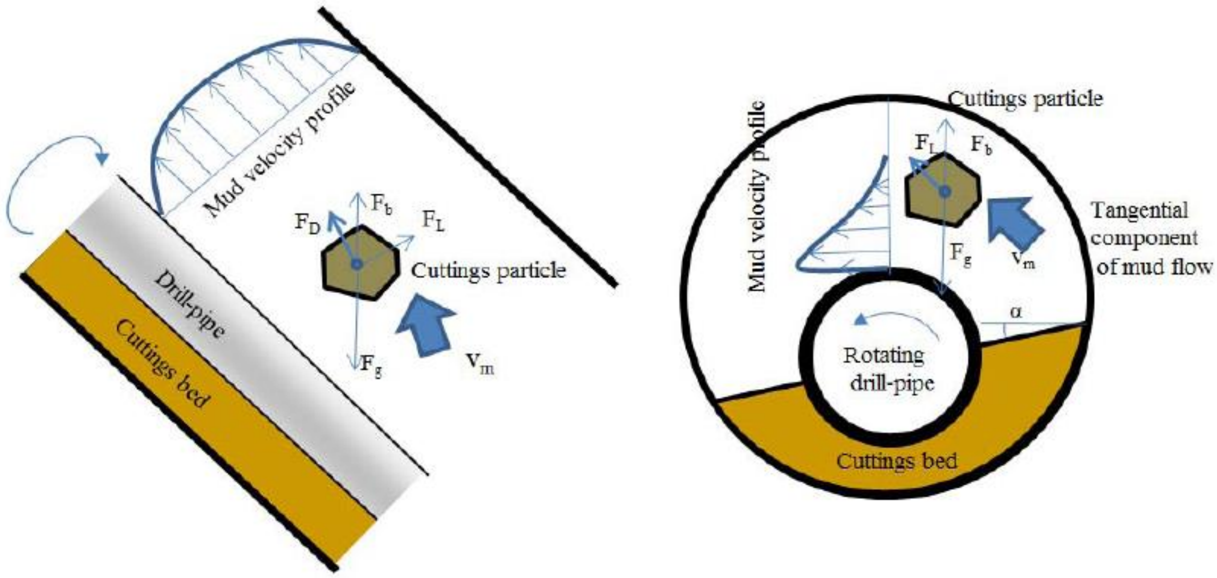


Figure 3.3b: Forces acting on a cutting particle in suspension [26]

Figure 3.4 illustrated the sizes of cutting obtained from conventional and Reelwell methods drilling. This thesis work will be limited to analyses the conventional types sized cutting.

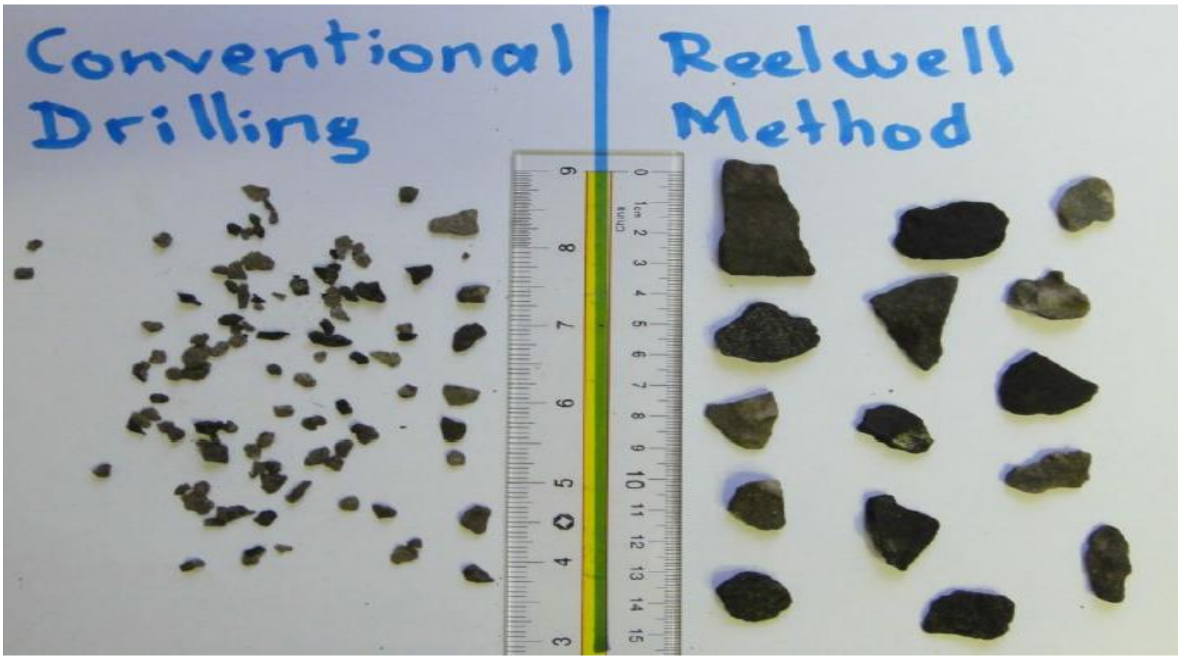


Figure 3.4: Cutting sizes and shapes [27]

How cuttings are transported?

Due to gravity, cuttings in deviated well have a tendency to settle and form cuttings beds on the low side wall. These cuttings are transported either as a continuous moving bed or in separated beds/dunes. Figure 3.5 is a schematic representation of the transport mechanisms for a range of well inclinations [28].

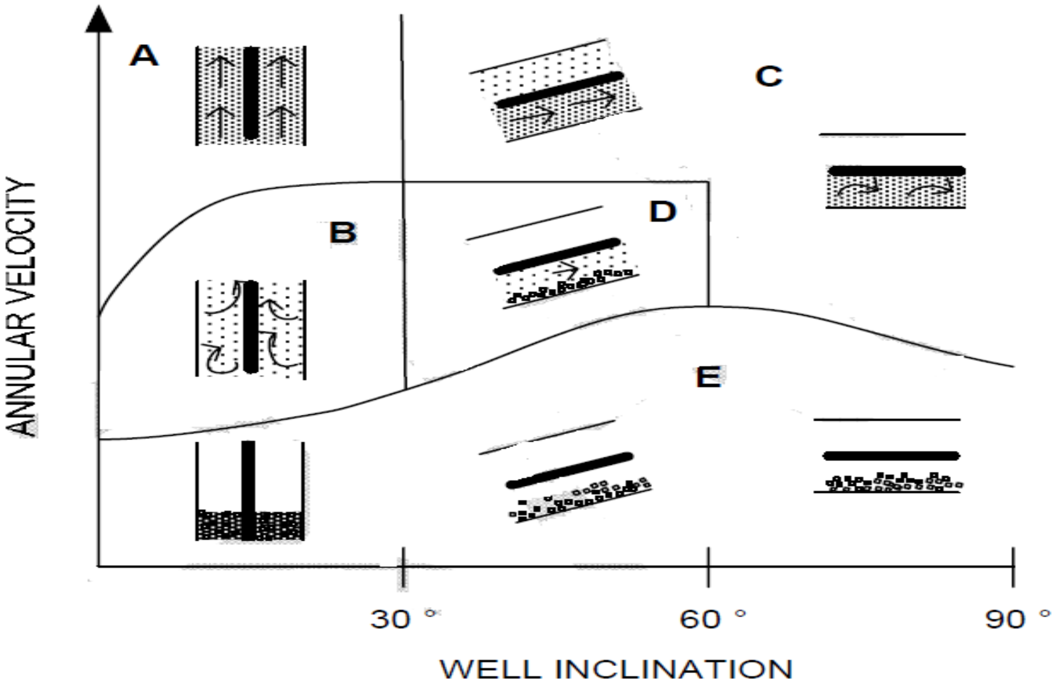


Figure 3.5: Cuttings transport mechanisms in vertical and deviated wells [28]

KEY

- ✓ A Zone 1 - Efficient hole cleaning
- ✓ B Zone 2 - Slow cuttings removal
- ✓ C Zone 3 - Good hole cleaning with moving cuttings bed
- ✓ D Zone 4 - Some hole cleaning – cuttings bed formed
- ✓ E Zone 5 - No hole cleaning

As shown in the figure, in well inclined less than 30°, one can observe that the cuttings are effectively suspended by the fluid shear and beds do not form (Zones 1 and 3). Above 30°, the cuttings can be deposited and form beds. The bed may slide back down (Zone 4). Rotating drill string disturbs the cuttings beds. The cuttings can then be exposed to the flowing drilling fluid towards the high side of the hole.

3.2.1 Bed height

Bed height is calculated based on the fundamental trigonometric relations. The model back the Wellplan™ simulator is not presented in the documentation. However, the following presents the model developed by Mingqin Duan et al. [29]. The authors have developed flow area from which one can calculate the bed deposition. Figure 3.6 illustrate circular pipe positioned at a certain eccentricity and bed deposition.

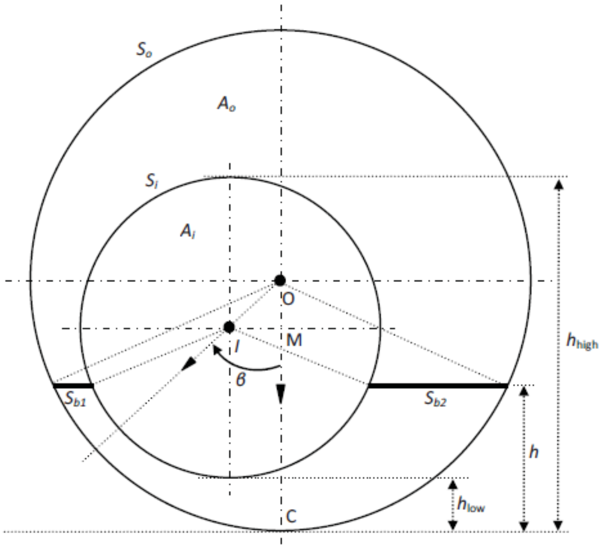


Figure 3.6: General well bore geometry configuration and cutting deposition [29]

Case 1: $h \le h_{low}$

$$A_f = R^2 ar\cos\left(\frac{h-R}{R}\right) + (R-h)\sqrt{R^2-(R-h)^2} - \pi r^2 \tag{10a}$$

Case 2: $h_{low} \le h \le h_{high}$

$$A_f = R^2 ar\cos\left(\frac{h-R}{R}\right) + (R-h)\sqrt{R^2-(R-h)^2} - \pi r^2$$
$$- \quad r^2 ar\cos\left(\frac{h-R+a_v}{R}\right) - (R-h-a_v)\sqrt{r^2-(R-h-a_v)^2} \tag{10b}$$

Case 3: $h \ge h_{high}$

$$A_f = R^2 ar\cos\left(\frac{h-R}{R}\right) + (R-h)\sqrt{R^2-(R-h)^2} \tag{10c}$$

Where R = radius of well/casing and r = radius of the drill string, h = bedding height.

3.2.2 Particle slip velocity /Terminal settling velocity

The particle slip velocity is an important parameter. It is defined as the velocity at which a particle tends to settle in a fluid because of its own weight. The slip velocity depends on the particle size, its geometry, its density, and fluid rheological properties. The carrying capacity of muds also is affected by the velocity profile in the annulus.

Force in the direction of flow exerted by the fluid on the solid is called ***drag***. Figure 3.7 shows a stationary smooth sphere of diameter D_P situated in a stream, whose velocity far away from the sphere.

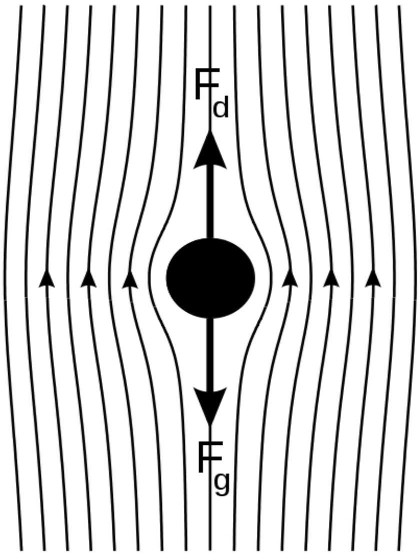


Figure 3.7: Drag force on a solid suspended in fluids [30]

If the annular flow velocity doesn't exceed the slip velocity, this often leads to problems related to cutting accumulations. To avoid such problems, we need to accurately predict the slip velocity in order to determine the appropriate flow rate for better cleaning operation.

The slip velocity is assumed to be equal to the terminal settling velocity of the particle in a stationary liquid. However, an assumption is questionable because of the complex motion of the particle in the annulus.

<u>Gravitational force</u>: This is the apparent weight of the particle, which is the apparent weight [35].

$$F_g = \pi \frac{d_p^3}{6}(\rho_p - \rho_f).g \tag{11}$$

Where d_p is particle size, ρ_p is density of particle and ρ_f density of fluid

<u>Drag force</u> **[**35]

$$F_D = \frac{\pi}{8} d_p^2 \rho_f v_s^2 .C_D \tag{12}$$

Where, Vs is solid Patrice velocity, and C_D is Drag Coefficient = *f*(Particle Reynolds No, Particle Shape). The drag coefficient as a function of particle Reynolds number is illustrated in Figure 3.8.

For terminal settling velocity, balancing the drag force and gravitational force, one obtains the settling velocity as:

$$F_D = F_g \tag{13}$$

$$v_s = \left(\frac{4.gd_p(\rho_p - \rho_f)}{3\rho_f .C_D} \right)^{0.5} \tag{14}$$

The experimental results of the drag on a smooth sphere may be correlated in terms of two dimensionless groups - the drag coefficient C_D and particles Reynolds number N_{ReP}:

Particle Reynolds No

$$N_{Rep} = \frac{\rho_f v_s d_p}{\mu} \tag{15}$$

μ is fluid viscosity

Case 1: For $1 < N_{Re} < 10^5$ (typically for non-smooth sphere), we may approximate the expression: [31]

$$C_D \approx \frac{24}{N_{Re}} \sqrt{1 + 0.2N_{Re} + 0.0003N_{Re}^2} \tag{16}$$

Case 2: For values $N_{Re} > 10^5$, C_D is about 0.1

Case 3: For sufficiently small grain particles, $N_{Re} < 1$, the drag coefficient is approximated as:

$$C_D \approx \frac{24}{N_{Re}} \tag{17}$$

This gives the settling velocity as:

$$v_s \approx \frac{g d_p^2 (\rho_p - \rho_f)}{18 \mu_{eff}} \tag{18}$$

(This expression is often referred to as Stokes' law)

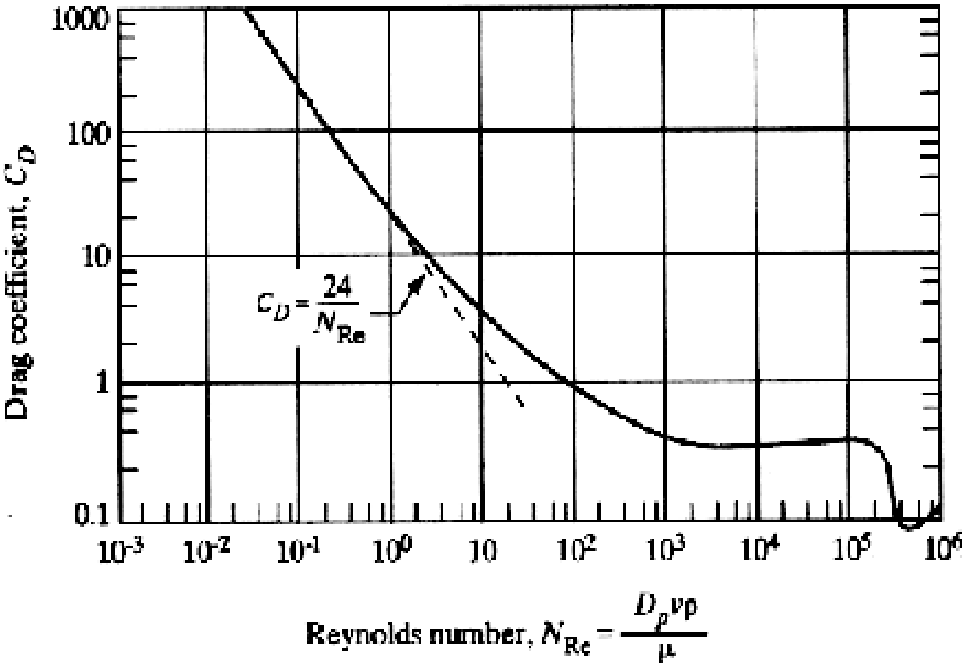


Figure 3.8: Drag coefficient vs Reynolds number [39]

3.2.3 Fluid velocity

The annular flow velocity is defined as the amount flow rate (Q) per the annular cross sectional area (A). The flow consists of solid phase and liquid phase. The solid phase is cuttings and the liquid phase indicates drilling fluid. To lift the drill cuttings vertically upward, the velocity of the fluid should be larger than the settling velocity. The fluid velocity (V_{fluid}) is given as

$$V_{fluid} = Q/Area \tag{19}$$

3.2.4 Transport velocity

A cutting particle exposed to an upward force due to the drilling fluid velocity and a downward force due to gravity. The rate at which a particle falls in stagnant fluid is called the terminal settling velocity or the slip velocity, V_{slip}. The net upward velocity V_T of the cutting in annulus is obtained by subtracting the slip velocity from the fluid velocity is then given by:

$$v_T = v_{fluid} - v_{slip}, \tag{20}$$

Where, V_{fluid} is the velocity of the fluid in the annulus given as Eq. 19.

3.2.5 Transport ratio

The hole cleaning is quantified using the cuttings transport ratio [F_T]:[2]

$$F_T = \frac{v_T}{v_{fluid}} \tag{21}$$

For positive cutting transport ratios the cuttings will be transported to the surface and for a slip velocity of zero, the cuttings will be transported at a velocity equal to the fluid velocity and the cuttings transport ratio will equal unity.

3.2.6 Reynolds number

Due to changing flow regimes Moore and Chien proposes different expressions for the slip velocity depending on the particle Reynolds number that is given in field units as: [2]

$$N_{\mathrm{Re}} = \frac{928\rho_f v_{slip} d_c}{\mu_a}, \tag{22}$$

where ρ_f is the fluid density, d_c is the diameter of the cutting particle and μ_a is the apparent viscosity.

3.3 Cutting transport models

3.3.1 Vertical Empirical model

Several investigators have proposed empirical correlations for estimating the cutting slip velocity experienced during rotary-drilling operations. The correlations of Moore [7] and Chien [6] are most commonly used.

The cutting transport efficiency in vertical wells is usually analyzed by computing the settling velocity, which is dependent on several factors such as:

- **Particle property:** Density, shape and size
- **Drilling fluid properties**: Fluid rheology, density and velocity
- **Hole configuration**: Inclination and size
- **Operational parameters**: Pipe rotation and eccentricity

3.3.1.1 Chien-model

Chien [6] presented two empirical correlations for the settling velocity of drill cuttings for rotary drilling operations: one for determination of the settling velocity of cuttings in all slip regimes and the other a simplified version for the turbulent-slip regime.

For mixtures of bentonite and water, the plastic viscosity can be used as the apparent viscosity, while for polymer-type drilling fluids; the apparent viscosity is calculated as shown below:

$$\mu_a = \mu_p + 300\frac{\tau_y d_s}{\overline{v}_a} \tag{23}$$

Where μ_a = apparent viscosity, μ_p = plastic viscosity (PV), τ_y = yield stress (YS) or yield point (YP) and d_s = diameter of drill string. Settling velocity or slip velocity is the velocity at which solid particles sink down through liquid. The empirical equation tried to correlate factors such as cutting size, cutting density, mud weight and viscosity of the mud to settling velocity.

The empirical equation for settling velocity V_{slip}:

$$v_{slip} = \begin{cases} 1.44\sqrt{d_c \dfrac{\rho_c - \rho_f}{\rho_f}}, N_{\mathrm{Re}} > 100 \\ 0.0075\left(\dfrac{\mu_a}{\rho_f d_c}\right)\left(\sqrt{\dfrac{36800 d_c}{\left(\dfrac{\mu_a}{\rho_f d_c}\right)^2}\left(\dfrac{\rho_c - \rho_f}{\rho_f}\right)+1}-1\right), N_{\mathrm{Re}} \le 100 \end{cases} \tag{24}$$

All correlations are given in field units and ρ_c is the density of the cuttings.

3.3.1.2 Moore's correlation

In order to calculate the slip velocity using this correlation, the apparent viscosity of the fluid is obtained by equating the annular frictional pressure loss equations for the power-law and Newtonian fluid models. The apparent viscosity is then given by [7]:

$$\mu_a = \frac{K}{144}\left(\frac{d_2 - d_1}{\bar{v}_a}\right)^{1-n}\left(\frac{2+\frac{1}{n}}{0.0208}\right)^n$$

The apparent viscosity is then used to calculate the Reynolds' number as follows:

$$\mathrm{N_{Re}} = \frac{928\rho_f v_{sl} d_s}{\mu_a} \tag{25}$$

For Reynolds' number greater than 300, the slip velocity can be calculated as:

$$\bar{v}_{slip} = 1.54\sqrt{d_s \frac{\rho_s - \rho_f}{\rho_f}} \tag{26}$$

For Reynolds' number less than 3, when flow is considered to be laminar, the slip velocity equation becomes:

$$\bar{v}_{slip} = 82.87\frac{d_s^2}{\mu_a}\left(\rho_s - \rho_f\right) \tag{27}$$

The friction factor is given as:

$$f = \frac{40}{N_{Re}} \tag{28}$$

For intermediate Reynolds numbers (3 <Re<300) corresponding to the transitional flow regime, friction factor and the slip velocity can be calculated as:

$$f = \frac{40}{\sqrt{N_{Re}}} \tag{29}$$

$$\bar{v}_{slip} = \frac{2.90 d_s \left(\rho_s - \rho_f\right)^{0.667}}{\rho_f^{0.333} \mu_a^{0.333}} \tag{30}$$

3.3.1.3 Zeidler's slip velocity correlation

Zeidler 1972 [34] has performed cutting transport experimental study and have generated a slip velocity correlation equation. The study shows that the pipe rotation and drilling muds produces changes in the recovery fractions. From the study the following relations were obtained to determine the settling velocity (V_s) of the drilled particles in a Newtonian fluid:

$2 \le N_{RE,p} \le 15$

$$V_s = 13.42 \frac{(\rho_s - \rho_l)^{0,782}}{\rho_l^{0.218}} \frac{d_{eq}^{1.35}}{\mu^{0,564}} \tag{31}$$

$15 \le N_{RE,p} \le 80$

$$V_s = 13.88 \frac{(\rho_s - \rho_l)^{0,612}}{\rho_l^{0.388}} \frac{d_{eq}^{0,836}}{\mu^{0224}} \tag{32}$$

$80 \le N_{RE,p} \le 1500$

$$V_s = 17.88 \frac{(\rho_s - \rho_l)^{0,516}}{\rho_l^{0.48}} \frac{d_{eq}^{0,548}}{\mu^{0.032}} \tag{33}$$

In the above relations, all values are in cgs units. From these relations the dependence of settling velocity on viscosity is seen to decrease with increasing Reynolds numbers. This indicates that the form drag becomes more predominant and the viscous drag becomes less significant with increasing Reynolds numbers.

3.3.2 High angle empirical model

3.3.2.1 Larsen's empirical model

Larsen 1990 [5] developed a high angle empirical correlation equation based on extensive experimental works. The study analyzed several factors that affected cutting transport in the annulus. The parameters considered for the study were angle of inclination, annular flow rate, mud rheology, eccentricity of drill pipe, cutting size, mud weight, drilling rate and rotary speed of the drill pipe. Larsen proposed three vital equations on the basis of experimental study. The first one was cuttings velocity while the second equation was slip velocity. The third equation is critical transport velocity which is the sum of the above mentioned equations

Critical velocity: The model of Larsen predicts the critical transport fluid velocity, v_{ctf} for an angle of deviation in the range 55^0-90^0 from vertical. This velocity is defined as the minimum fluid velocity required to maintain a continuously upward movement of the cuttings.V_{ctf} is found by adding the average cuttings travelling velocity, V_{ct} to the equivalent slip velocity, v_{es}:

$$v_{ctf} = v_{ct} + v_{es} \tag{34}$$

The average cuttings travelling velocity can be expressed through a mass balance between the cuttings generated by the drill bit and the cutting mass transported by the fluid:

$$\rho_c Q_i = \rho_c A_{ann} C_c v_{ct} \tag{35}$$

Here Q_i is the volumetric injection rate, A_{ann} is annulus area, C_c is the cutting concentration, and v_{ct} is the cuttings transport velocity.

Cutting transport velocity (V_{cut}) : By converting the volumetric injection rate to rate of penetration, ROP, and expressing the cutting concentration in terms of percent, C_{cp}, we get the following expression for v_{ct}:

$$v_{ct} = \frac{ROP}{36\left(1-\left(\frac{D_p}{D_h}\right)^2\right)C_{cp}}, \qquad (36)$$

Where, the cutting concentration (C_{cp}) at critical transport fluid velocity is:

$$C_{cp} = 0.01778 \cdot ROP + 0.505 \qquad (37)$$

Equivalent slip velocity (V_{eslip}):

The equivalent slip velocity is given by:

$$\bar{v}_{eslip} = \begin{cases} 0.00516 \cdot \mu_a + 3.006 \text{ if } \mu_a < 53 \text{ cp} \\ 0.02554(\mu_a - 53) + 3.28 \text{ if } \mu_a > 53 \text{ cp} \end{cases} \qquad (38)$$

the apparent viscosity is given by:

$$\mu_a = \mu_0 + \frac{5\tau_y (D_H - D_{P})}{V_{ctf}} \qquad (39)$$

Where, $D_{H=}$ diameter of hole, D_P= diameter of pipe, μ_p = plastic viscosity τ_y =yield stress.

If the annular fluid velocity is lower than v_{ctf}, cutting will start to accumulate, and form a bed in the well bore. We then get the following expression for the area occupied by cuttings:

$$A_{bed} = A_{ann} - A_{open} = A_{ann}\left(1 - \frac{Q_{pump}}{Q_{ctf}}\right) \qquad (40)$$

Correlation factors: It is observed from experimental data that the model over predicts the bed heights, and the over prediction increases for increasing mud viscosity. To compensate for this, Larsen introduced a correction factor based on regression analysis of the experimental data. Bed correction factor (C_{bed}) in terms of apparent viscosity:

$$C_{bed} = 0.97 - 0.00231\mu_a \qquad (41)$$

$$A_{bed} = A_{nn} \cdot C_{bed} \left(1 - \frac{Q_{pump}}{Q_{ctf}} \right) \tag{42}$$

The general equivalent slip velocity can be expressed as:

$$v_{es} = C_{ang} C_{cd} C_{mw} \bar{v}_{eslip} \tag{43}$$

The angle of inclination correction factor (C_{ang}) is given by:

$$C_{ang} = 0.0342\alpha - 0.000233\alpha^2 - 0.213 \tag{44}$$

The cutting size correction factor (C_{cd}) is given by:

$$C_{cd} = -1.04 d_a + 1.286 \tag{45}$$

Here d_a is the average cuttings diameter.

The mud weight correction factor (C_{mw}) is given by:

$$C_{mw} = \begin{cases} 1 - 2.779 \cdot 10^{-4} (\rho_f - 1042.5) \text{ if } \rho_f > 1042.5 \text{ kg/m}^3 \\ 1 \text{ else} \end{cases} \tag{46}$$

Larsen's experimental and simulation work clearly shows that:

- **Cutting size:** Cuttings with smaller size are difficult to transport for high angles while the contrary is true for low angles.
- **Mud density:** Increasing mud weight resulted in decreasing critical transport velocity.
- **Drill pipe rotation:** Pipe rotations show no effect on cutting transport velocity. However, several other experimental works shows RPM effect even including WellPlan™ simulator.
- **Drilling rate (ROP):** The higher drilling rate required higher critical transport velocity.

3.3.2.2 Hopkins method -Critical Flow rate

Hopkins 1995 [33] developed a model used to determine the critical cutting transport velocity. The method use slip velocity slip velocity chart. The slip velocity is calculated using analytical procedure.

$$V_s = \frac{(\rho_s - \rho_m)^{0.667} x 175 x d_c}{\rho_m^{0.333} x \mu^{0.333}} \tag{47}$$

Where, ρ_s is density of solid, ρ_m is density of mud, d_c = diameter of cutting and μ is apparent viscosity

Step 2: The correction term that includes the effect of mud weight on slip velocity is estimated from Eq. 48.

$$FMW = 2.117 - 0.1648 x \rho_m + 0.003681 x \rho_m^2 \tag{48}$$

$$V_s = FMW x V_{sv} \tag{49}$$

Step 3: Using the mud density corrected slip velocity, the minimum cutting transport velocity is estimated as:

$$V_{\min} = V_s \cos\theta + V_2 \sin\theta \tag{50}$$

Step 4: In Step 3, V_2 is calculated using formula;

$$V_2 = C * \left[\left(\frac{\rho_s - \rho_m}{\rho_m} \right) g^3 \left(\frac{d_h - d_p}{12} \right)^3 \right]^{\frac{1}{6}} \tag{51}$$

Step 5. Finally, the minimum flow required in gal/min is obtained using the formula below;

$$Q_{crit} = 0.04079 (d_h^2 - d_p^2) x V_{\min} \tag{52}$$

As can be see, the application of this method is very simple to understand and can be applied for field and laboratory purposes.

3.3.2.3 Rubiandini's modified slip velocity correlation

Rubiandini [8] made attempts to couple the mud weight, RPM and well inclination effects on cutting transport model. Basically he used the Moore's correlation equation, on which the modification was performed. According to the author, the minimum drilling fluid flow velocity is the sum of the slip velocity and the cutting falling velocity. Figure 3.9 illustrates the minimum velocity (V_{min}) calculation Procedure using Rubiandini's correlation

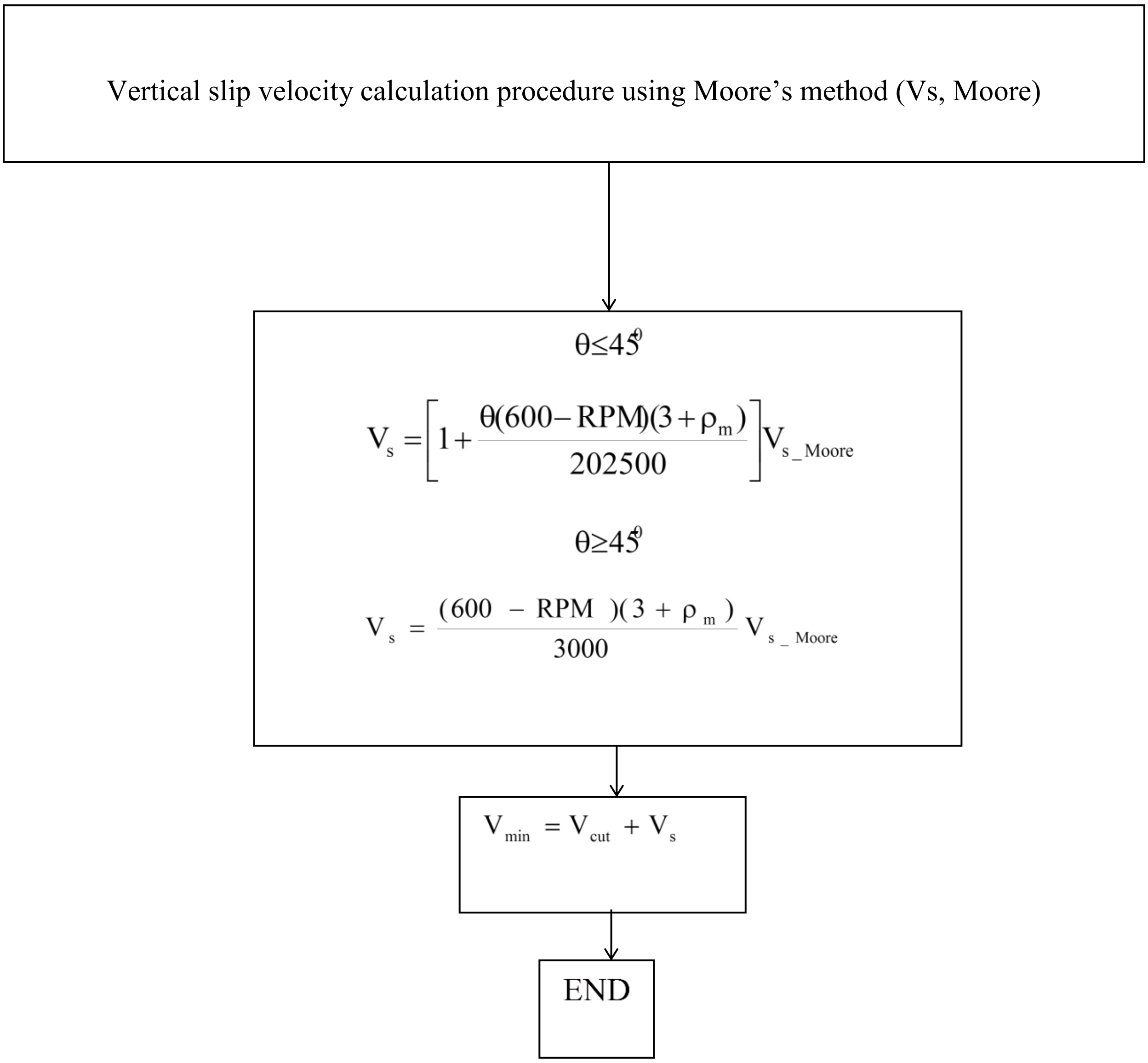


Figure 3.9: Algorithm to couple mud density and well inclination on cutting transport model

3.3.3 Mechanistic model

Ramadan et al (2001, 2003) [35, 36] have developed a mechanistic model used to describe the particle transport phenomenon. Figure 3.10 shows the particle deposition at the bed of a tube.

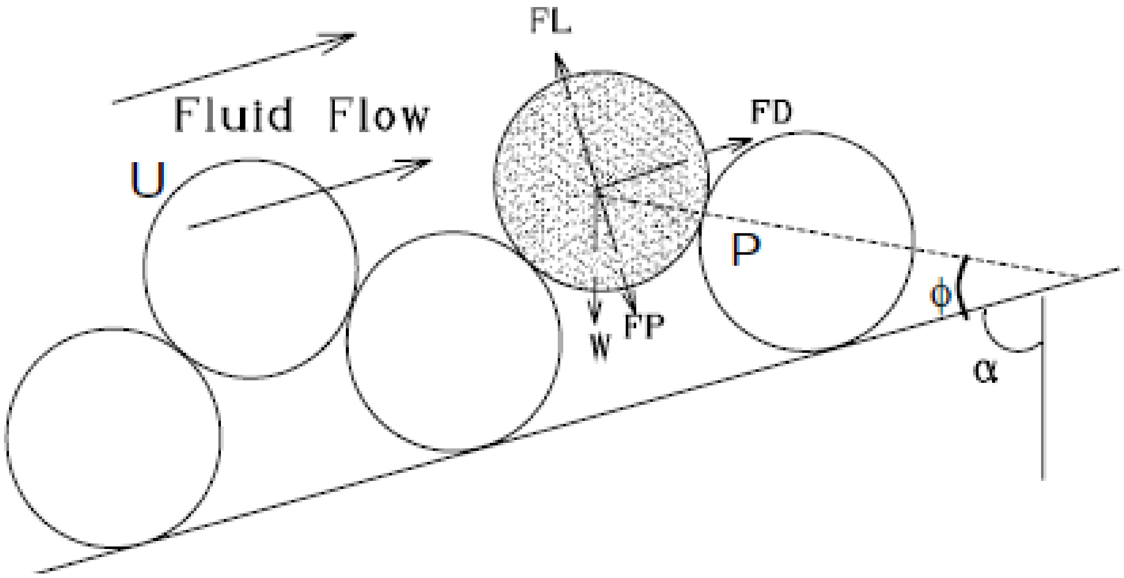


Figure 3.10: Forces acting on a single particle at an active erosion site of a cuttings bed [35]

During lifting, a cuttings bed particle starts its motion in the direction normal to the bed and move up into the region where the axial mud velocity carries the cuttings downstream. Lifting occurs when the lift force overcomes the plastic force and the component of force of gravity in the direction of the lift. Consequently, if we balance the forces in the y direction then the condition for lift will be:

$$F_y = F_L - F_P - W \sin\alpha \geq 0 \tag{52}$$

The models used for evaluating the forces in Equation 52 is presented in Table 3.1

Force	Model equation
Lift	$\frac{\pi}{8} d_p^2 C_L \rho u^2$
Drag	$\frac{\pi}{8} d_p^2 D_R C_D \rho u^2$
Plastic	$\frac{\pi}{4} d_p^2 \tau_y$
Net gravity	$\frac{\pi}{6} d_p^3 (\rho_s - \rho) g$

Table 3.1: Model equations used in particle mechanics modelling [35, 36]

By substituting the model presented in Table 3.2 into Equation 3.2 the net upward force can be expressed as:

$$F_y = \frac{\pi}{2} d_p^2 \rho_f \left(\frac{f_L C_L U^2}{4} - \frac{\tau_y}{2\rho_f} - \frac{d_p \sin\alpha (s-1) g}{3} \right) \tag{53}$$

The criteria for lifting a particle from the surface of a bed is that the term in brackets in Equation 53 must be positive. Therefore, the critical velocity that is sufficient to suspend a cuttings particle can be estimated as:

$$U = \left(\frac{2\tau_y}{f_L C_L \rho_f} + \frac{4 d_p \sin\alpha (s-1) g}{3 f_L C_L} \right)^{0.5} \tag{54}$$

The critical velocity in Equation 54 is a function of the lift coefficient, which is by itself a function the critical velocity. Therefore, the determination of the critical velocity requires an iterative process.

$$U = \left(\frac{6\tau_y \cos\phi + 4 d_p g (s-1) \sin(\phi + \alpha)}{3(D_R C_D \sin\phi + f_L C_{LE} \cos\phi)} \right)^{0.5} \tag{55}$$

Ramadan [36] has performed laboratory scale cutting transport study. He compared the model against the measured data. Figure 3.11 shows the results. As shown the higher particles require a higher transport velocity.

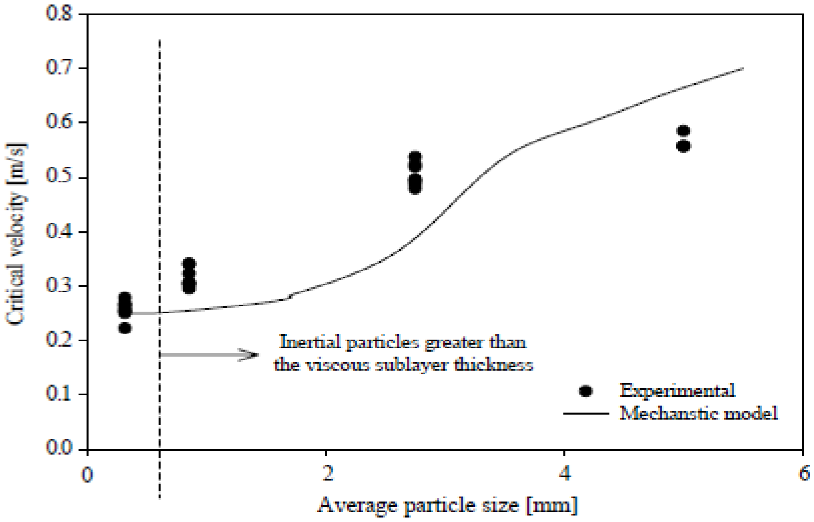


Figure 3.11: Comparison of model prediction and experimental data [35,36]

The pattern of critical velocity for lifting and rolling that are shown in Figure 3.12 obviously indicates the superiority of one mechanism over the other one. For that reason, lifting mechanism is highly expected to occur at low angle of inclination (less than 15 degrees) but rolling takes place in both intermediate and near horizontal angles. Clark and Bickham [20] has also developed a mechanistic model and they have also reported that their model capture some of the experimental data quite well

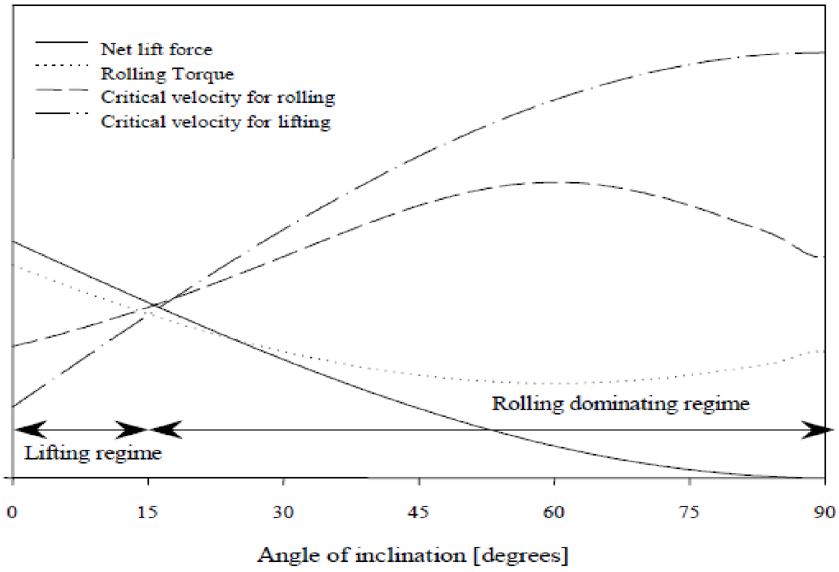


Figure 3.12: Various forces as a function of well inclination [36]

As can be seen from the figure, the lifting force reduces as the well inclination increasing. At the same time the rolling torque reduces and then the torque begins to recover

4 Cutting transport simulation

4.1 Introduction

During planning phase, the Hole Cleaning model is used to predict the critical (minimum) annular velocities/flow rates required to remove or prevent a formation of cuttings beds during a directional drilling operation.

In this thesis work, simulation was carried out in order to analyze the effect of parameters on the cuttings concentration percentage, bed height, and critical transport velocity flow rate as a function of well inclination and annular diameters.

For the analysis, we used hole cleaning parametric to determine the effect of varying parameters, including hole/string geometry and varied flow rate using the varied hole-geometry.

4.2 Theory of cutting transport back the WellPlan™ simulator

This mathematical model is based on the analysis of forces acting on the cuttings. It can be used to predict the critical (minimum) flow rate required to remove or prevent the formation of stationary cuttings beds during a directional drilling operation.

This model has been validated with extensive experimental data and field data [3]. For more information see Hole Cleaning Model, see Appendix B. Basically the model looks like Larsen's model presented in section §3.3.2.1. However, the WellPalan^{TM} software model includes more physics, which could capture hole cleaning phenomenon.

4.3 Description of Simulation arrangement

The cutting transport simulation was performed on 11003ft deviated well geometry. For parametric sensitivity study two well configurations were considered,

- Part I: A real well geometry was considered.
- Part II: A constant well inclination was oriented from vertical to horizontal.

The cased hole is 4012ft and the open hole is 6990ft length. The details are given in Table 4.1. The string consists of drill pipe and Bottom Hole assembly component data. The detail of the geometries and grading is given in Table 4.2.

Hole data (Casing + Open hole)

	Section type	**Measured Depth (ft.)**	**Length (ft.)**	**Shoe Measured Depth (ft.)**	**Id (In)**	**Drift (In)**	**Effective Hole Diameter (In)**	**Friction factor**	**Linear Capacity (bbl/ft)**	**Excess (%)**	**Item Description**
1	Casing	4012.5	4012.5	4012.5	12.250	12.459	12.615	0.25	0.1458		13 3/8in, 54.5ppf, J-55
2	Open Hole	11003.0	6990.50		12.250		12.250	0.30	0.1458	0.00	

Table 4.1: Hole data (Casing + Open hole)

Drill String data (Drill pipe + BHA)

Type	Length (ft)	Depth (ft)	Body	Stabilizer/tool joint					Weight (ppf)	Material	Grade	Class
			OD (in)	ID (in)	Avg.joint Length (ft)	Length (ft)	OD (in)	ID (in)				
Drill pipe	10445	10445.00	5.0	4.276	30.00	1.42	6.406	3.75	22.26	CS_API 5D/7	E	P
Heavy weight Drill pipe	120.0	10565.0	6.625	4.5	30.00	4.00	8.25	4.5	70.50	CS_1340 MOD	1340 MOD	
Hydraulic Jar	32.00	10597	6.5	2.75					91.79	CS_API 5D/7	4145H MOD	
Heavy weight Drill pipe	305.0	10902	5.0	3.0	30.00	4.00	6.50	3.063	49.7	CS_1340 MOD	1340 MOD	
Bit sub	5.00	10907	6.0	2.4					79.51	CS_API 5D/7	4145H MOD	
MWD tool	85.00	10992	8.0	2.5					154.36	SS_15-15LC	15-15LC MOD	
Integral blade stabilizer	5.00	10997	6.25	2.0		1.00	8.453		93.72	CS_API 5D/7	4145H MOD	
Bit sub	5.00	11002	6.0	2.4					79.51	CS_API 5D/7	4145H MOD	
Tri-cone bit	1.00	11003	10.625						166.0			

Table 4.2: Drill String data (Drill pipe + BHA)

Temperature gradient

The thermodynamics states of a system described by temperature and pressure. Therefore, for the simulation, geothermal gradient was constructed. The surface ambient and the geothermal gradient were 80 ^{o}F and 1.5 ^{o}F/100ft respectively. The geothermal profile is shown in Appendix C

Survey

The inclination and azimuth of the well data is attached in Appendix C.

4.4 Simulation results-Part I: Real well geometry

4.4.1 Description of well arrangement

The well construction and drilling string elements are given in Table 4.1 and Table 4.2. The survey data (measured depth, inclination and azimuth) are given in Appendix C.

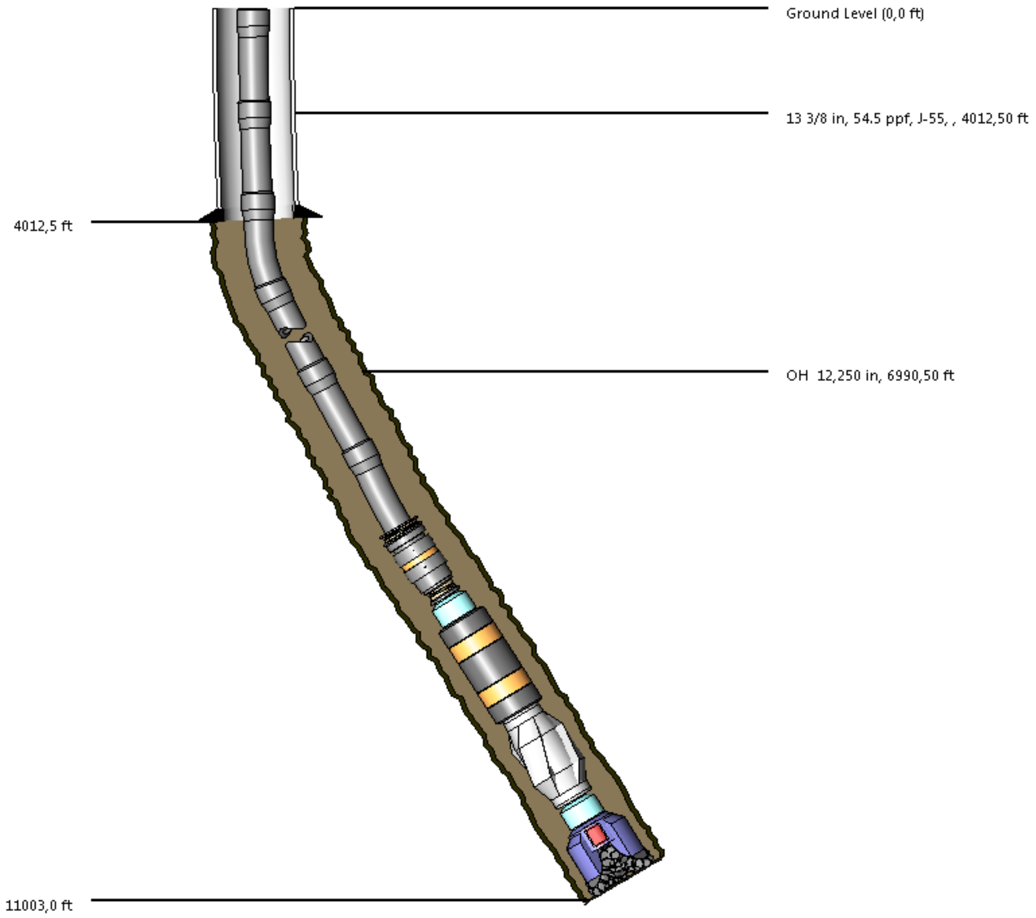
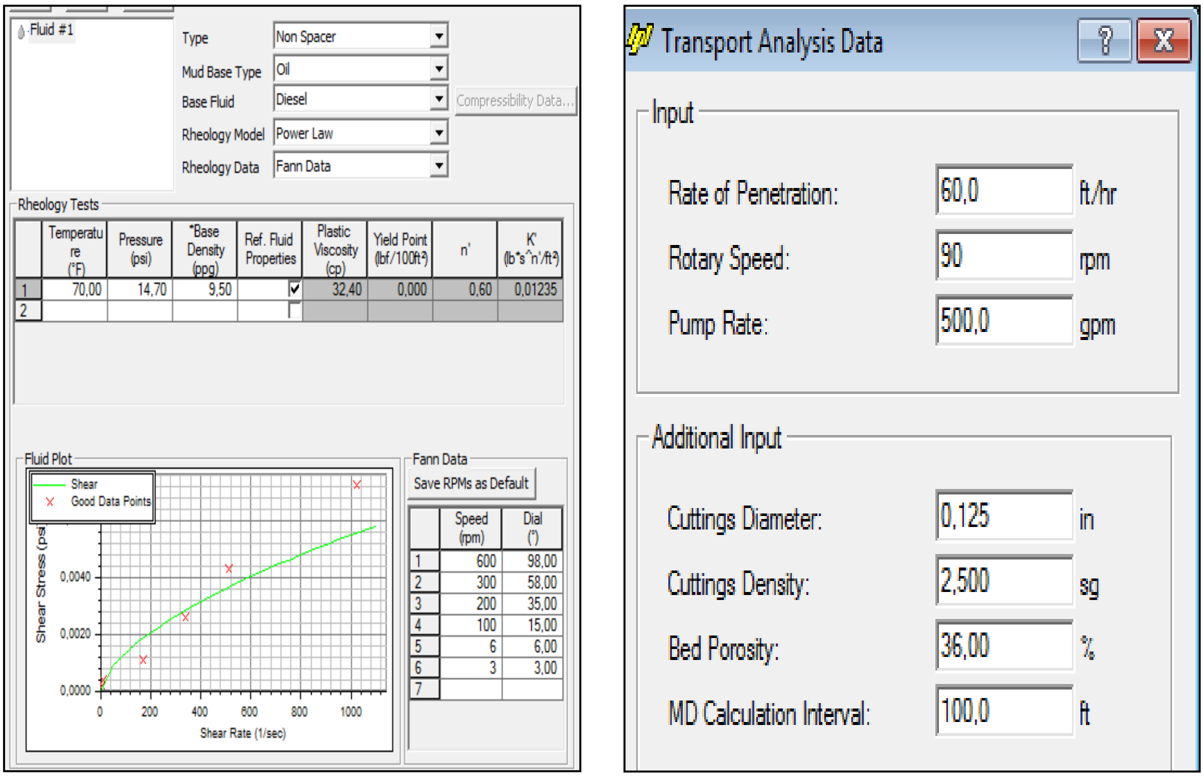


Figure 4.1: Real well geometry arrangement used for cutting transport simulation

4.4.2 Description of drilling fluid and transport analysis data

In this well geometry higher viscous Oil based mud (OBM) was used to evaluate the cutting transport phenomenon. The operational parameters and the cutting properties are given in Figure 4.2.



Type: Non Spacer
Mud Base Type: Oil
Base Fluid: Diesel
Rheology Model: Power Law
Rheology Data: Fann Data

Rheology Tests

	Temperature (°F)	Pressure (psi)	*Base Density (ppg)	Ref. Fluid Properties	Plastic Viscosity (cp)	Yield Point (lbf/100ft²)	n'	K' (lb*s^n'/ft²)
1	70,00	14,70	9,50	☑	32,40	0,000	0,60	0,01235
2				☐				

Fann Data

	Speed (rpm)	Dial (°)
1	600	98,00
2	300	58,00
3	200	35,00
4	100	15,00
5	6	6,00
6	3	3,00
7		

Input

Rate of Penetration: 60,0 ft/hr
Rotary Speed: 90 rpm
Pump Rate: 500,0 gpm

Additional Input

Cuttings Diameter: 0,125 in
Cuttings Density: 2,500 sg
Bed Porosity: 36,00 %
MD Calculation Interval: 100,0 ft

Figure 4.2: Rheology and cutting transport analysis data WellPalan^{TM}'s input box [3]

4.4.3 Result analysis

4.4.3.1 Effect of well inclination

Figure 4.2 is the simulation result carried out on the real well geometry (i.e Figure 4.1). As can be seen on the figure below, at around 4000 ft the inclination began to change and gradually increasing and reaching 26 deg at around 6000 ft. The simulation result shows that cutting volume increases from 0% to 25 % and bed height increases from 0 inch to 4.7 inch as well inclination increases from vertical/near vertical to 35deg. The result in general shows that the hole-cleaning problem increases as well inclination increases. In other words, a higher flow rate is required for highly inclined well. The effect of azimuth also simulated and the result shows that azimuth has no effect on hole-cleaning at all.

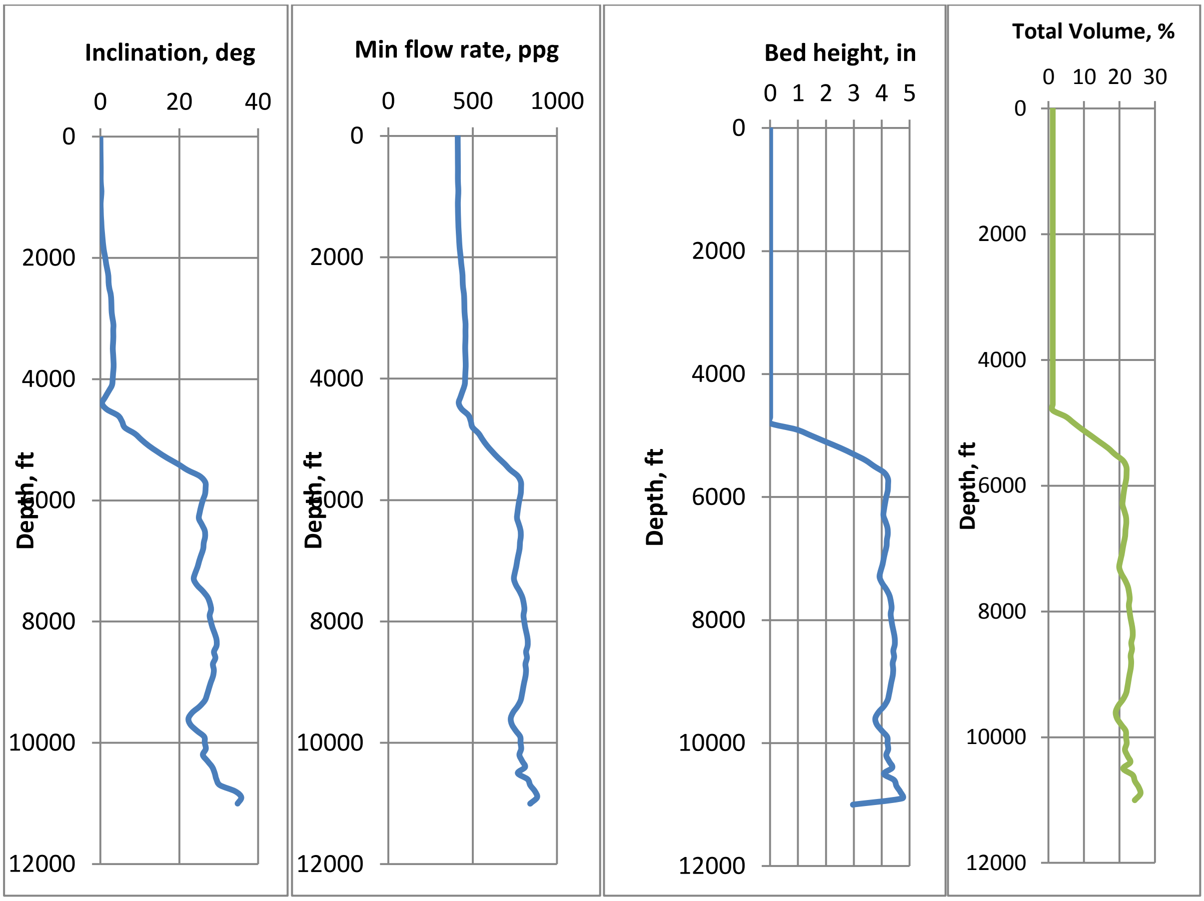


Figure 4.3: Simulation results in real well geometry

4.4.3.2 Effect of rheology model

There are several rheology models available in literature. Some of the most commonly used models are reviewed in section § 3.1. These models are implemented in WellPalan™ simulator. In this thesis work, the choice of rheology model on cutting transport phenomenon is analyzed in the real well geometry (Figure 4.1). For the analysis Bingham and Power law models were considered.

Figure 4.4 shows the comparison of the effect of rheology model on cutting deposition behavior. As can be seen, on the figure, in vertical and near vertical well geometry there is no difference between the results obtained from the two rheology models. However, as well deviation increases, the results shows that the use of Bingham rheology model predicts about 8.5% lower than the Power law rheology model.

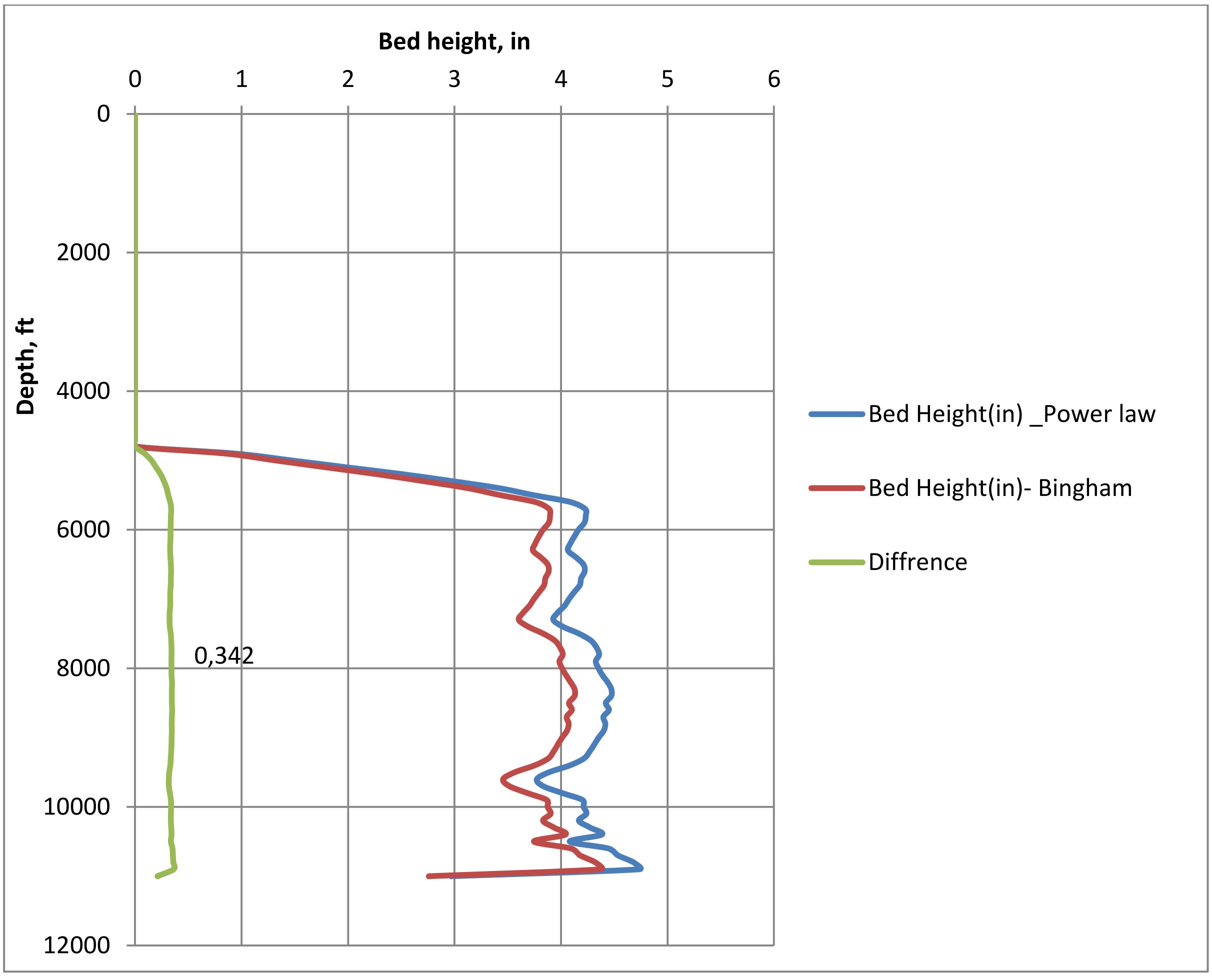


Figure 4.4: Effect of rheology model on cutting deposition behavior

4.5 Simulation results-Part II- Parametric sensitivity analysis

4.5.1 Description of well arrangement

The second part of simulation (Part II) is to investigate the effect of parameter on cutting transport behavior. For this a constant well inclination was analyzed as illustrated in Figure 4.5. As shown on the figure, the well is inclined from vertical to horizontal and the pipe is in concentric annuli.

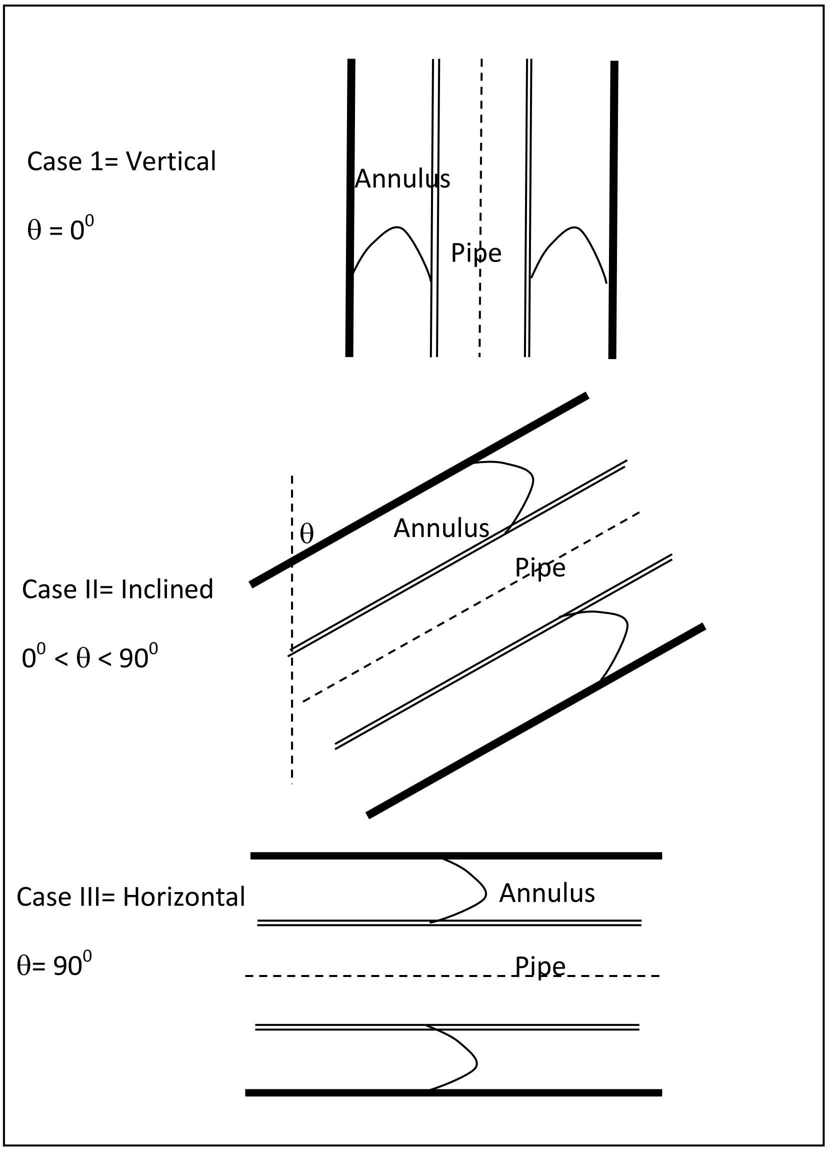
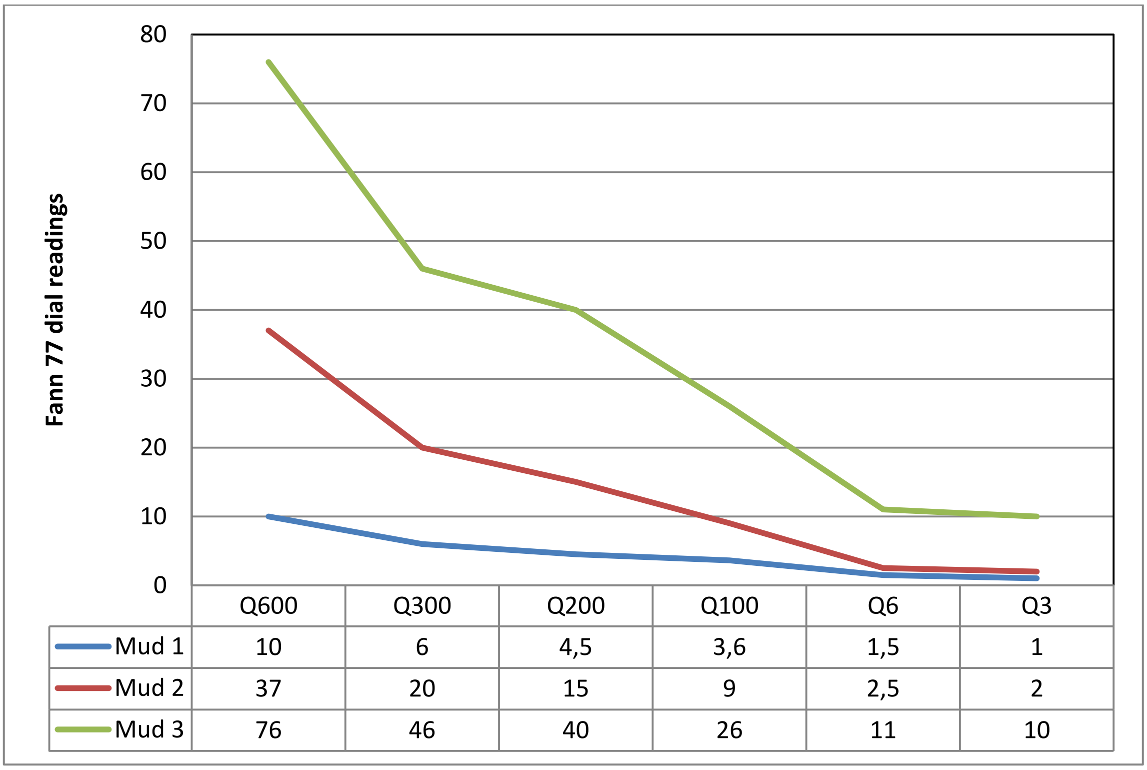


Figure 4.5: Fluid and particle dynamics in concentric well geometry annuli of various inclinations.

4.5.2 Description of mud system

Three water based mud systems were used for the investigation. The density of mud #1, mud #2 and mud #3are 68, 64 and 69pcf respectively. The Fann 77 rheometer data is shown in Figure 4.6. The gel strength (10sec/10min values) of the mud systems are (2.53/3), (2/2.5), and (4/5) lb/100sqft respectively



	Q600	Q300	Q200	Q100	Q6	Q3
Mud 1	10	6	4,5	3,6	1,5	1
Mud 2	37	20	15	9	2,5	2
Mud 3	76	46	40	26	11	10

Figure 4.6: Rheological properties of the Fann 77 dial reading of mud systems

4.5.3 Operational parameters effects Analysis

Several laboratory scale experimental studies have shown that drilling operational parameters have effect on hole-cleaning. However, this section analyzes the sensitivity of rotational velocity and rate of penetration with respect to well inclination.

4.5.3.1 Effect of rate of penetration (ROP)

During drill bit optimization study, the higher ROP is the better in order to drill faster and reduces cost. It is well known that the higher ROP increase the cutting volume in wellbore. The higher cutting concentration leads to increasing the density of mud, which increase the effective circulation density. It is therefore, important to clean the hole as effectively as possible. In this thesis work, the sensitivity of the cutting transport with respect to the ROP was studied. For the investigation, mud system #3 was considered. The density and the size of the cutting were 2.145sg and 0.25in respectively. The drilling string rotational velocity was 50RPM. Figure 1 shows the simulation result for the 30, 50 and 80ft/hr. As can be seen, the higher ROP requires more flow rate to clean the hole. This is because the higher the ROP generates more cuttings in the wellbore.

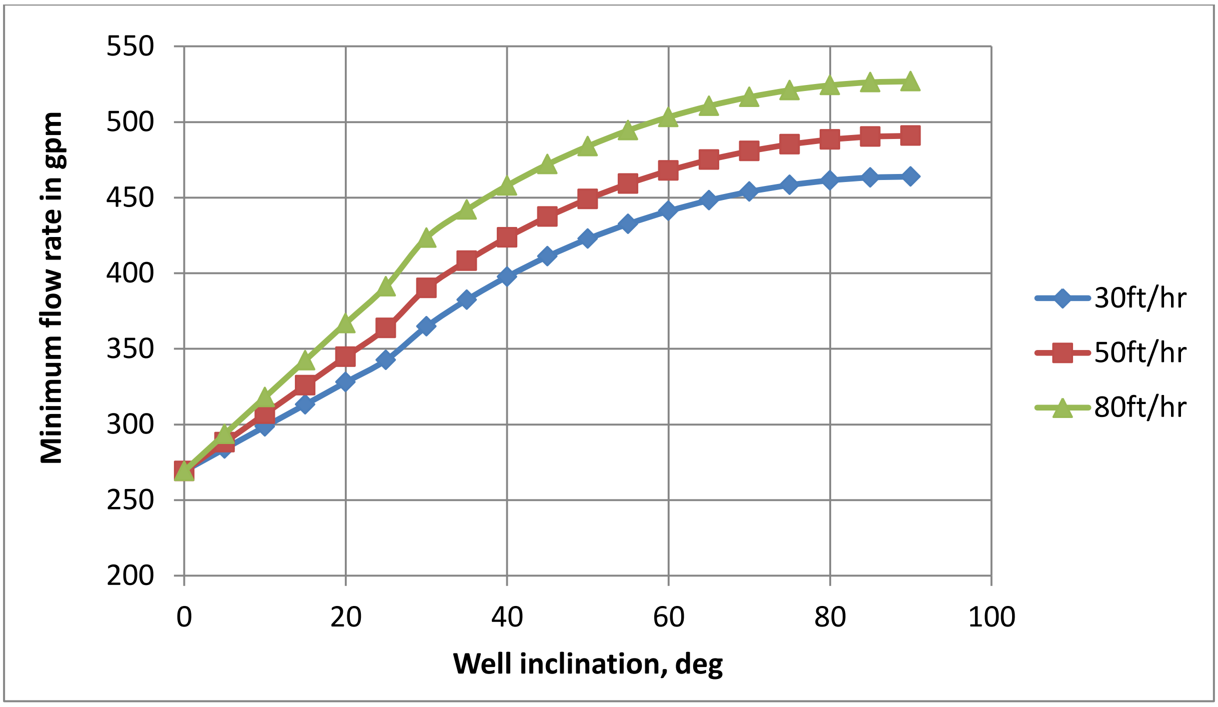


Figure 4.7: Effect of ROP on cutting transport

Figure 4.8 shows the relative % change in minimum hole cleaning flow between the simulated results presented in Figure 4.7. The analysis shows that when the drilling rate increases from 30ft/hr to 50ft/hr there is an increase minimum flow rate of about 5 %, while when the rate of drilling increases to 80 ft/hr the need for minimum flow rate increases by about 12% on average. Larsen (1990) [5] came to a similar conclusion on the impact of drilling rate. He has found out that doubling drilling rate from 27ft/hr to 54ft/hr needs an average increase in flow rate about 6-7%.

One can also observe that for an increase in ROP from 30ft/hr to 80ft/hr. the % increase in flow rate becomes peak (16%) at around 30 deg and gradually decreasing towards 55 deg. Then it begins to level out at 14 % for larger inclination. When ROP increases from 30ft/hr to

50ft/hr, the flow rate shows increasing by about 7% at 30 deg and levels out to 6 % after 55 deg. Generally speaking, it seems that relative flow rate increment is not sensitive to changes in inclination for larger well inclinations.

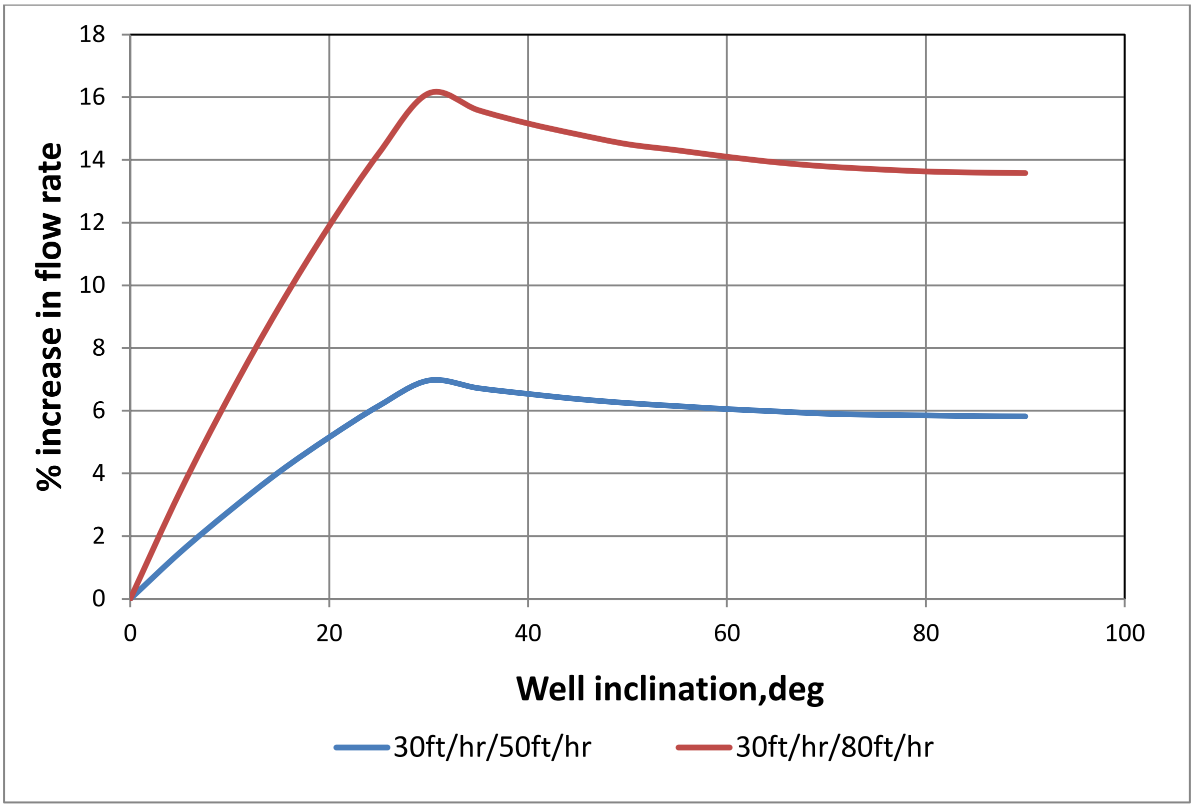


Figure 4.8: % Relative change between ROP's effects on flow velocity

4.5.3.2 Effect of rotational speed (RPM)

As pipe rotates, it reduces eccentricity and also alters the velocity distribution as illustrated in Figure 3.3b [26]. A rotating pipe drags cuttings from the low side of annulus to the high side. Several experimental at laboratory scale on the effect of RPM are documented in literature. In modeling both the Larsen (1997)[32] and other mechanistic model (Clark & Bickham, 1994 [20] don't consider the effect of RPM. Rubiandini (1999) [8] made an attempt to couple the effect of RPM. Larsen, however, asserted in his studies that pipe rotation does not have an effect on critical flow requirements for positive eccentricity. He tested three different pipe rotations; 0, 50, and 100 rpm to investigate the impact on cutting transportation. On the other hand, Bassal (1995) [37] concluded pipe rotation has a moderate to significant effect on hole cleaning.

In this thesis the effect of RPM investigated by considering 12.5 ppg mud system, which has the plastic viscosity =17.52cP, and YS =2.43lbf/100sq ft. The drilling rate of penetration was 50ft /hr. the cutting density and size are 2.145sg and 0.25 in respectively.

For muds, rotation of the centered as well as eccentric drill pipe generally showed increasing transport with higher rotary speeds. In water, however, drill pipe rotation caused a slight decrease in transport. In all cases, the effects were slight as shown in Figure 4.9. In the rage of 0-30 deg, the effect of RPM shows insignificant changes. For the angle 30 to 90deg, the effect is moderate showing that RPM positive in hole cleaning. The minimum flow rate for the drilling pipe at rest (0 rpm) increases sharper than for pipe rotation 50 rpm and 100 rpm. For inclination angles more than 30 degrees the graph gradually increasing and it is flattened for angles more than 60 degrees.

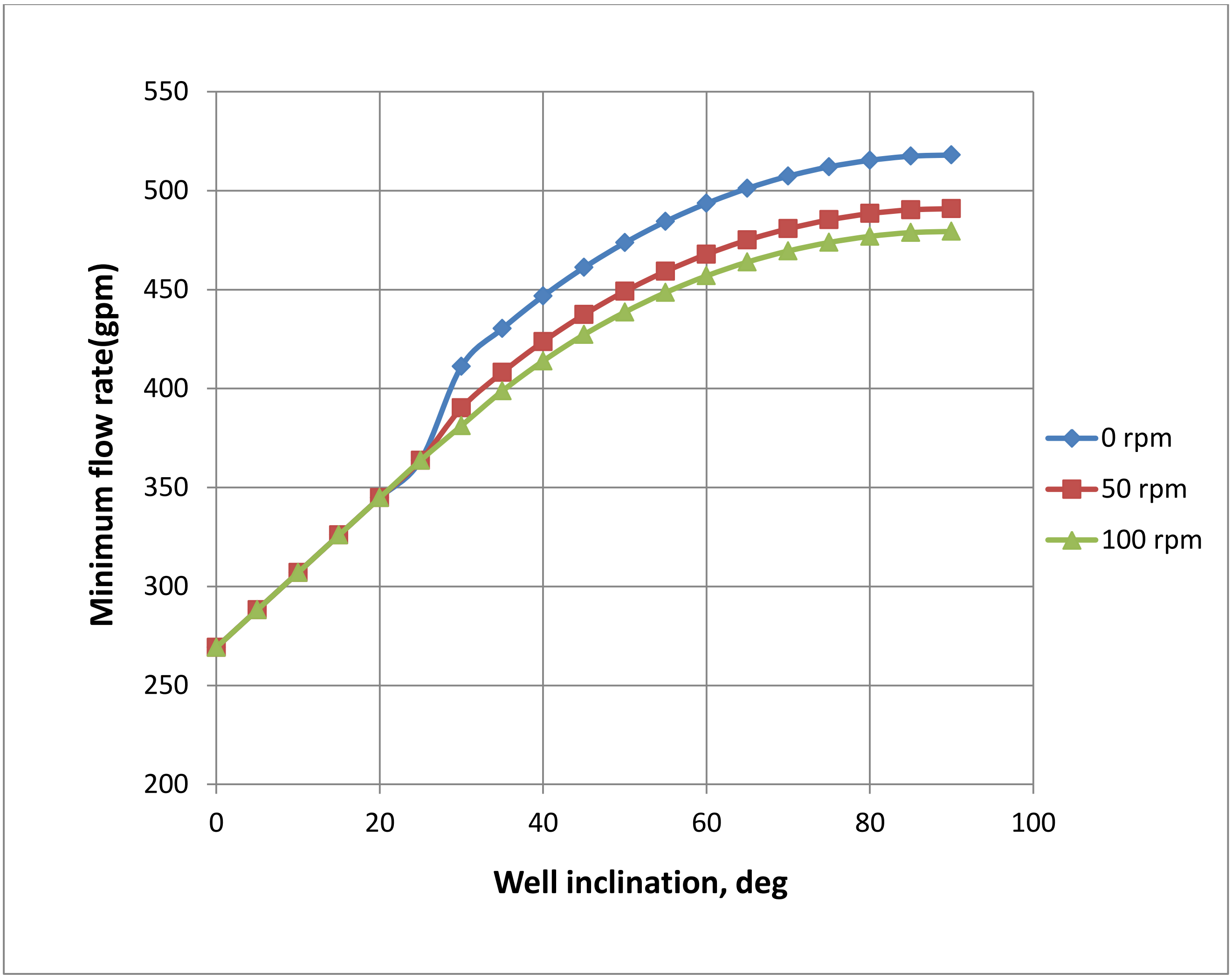


Figure 4.9: Sensitivity of RPM on cutting transport

As shown in figure 4.10, impact of pipe rotation is negligible for inclination less than 25 deg. Then, the graph sharply shows increasing and attaining maximum value at around 30 deg. After a small reduction in gradient at around 35, deg then the graph becomes flat.

It is evident from the graph that by increasing the pipe rotation from stationary state to 50 and 100 rpm resulted in a reduction in the demand of flow rate of 5% and 7% respectively. Increasing the pipe rotation to 100 RPM gives a reduction of only 2% in flow rate. Given the demand for power at such high speed, the reduction gained by increasing the rotation does not seem beneficial. For inclination larger 30deg, the impact of pipe rotation is almost uniform irrespective of hole inclination.

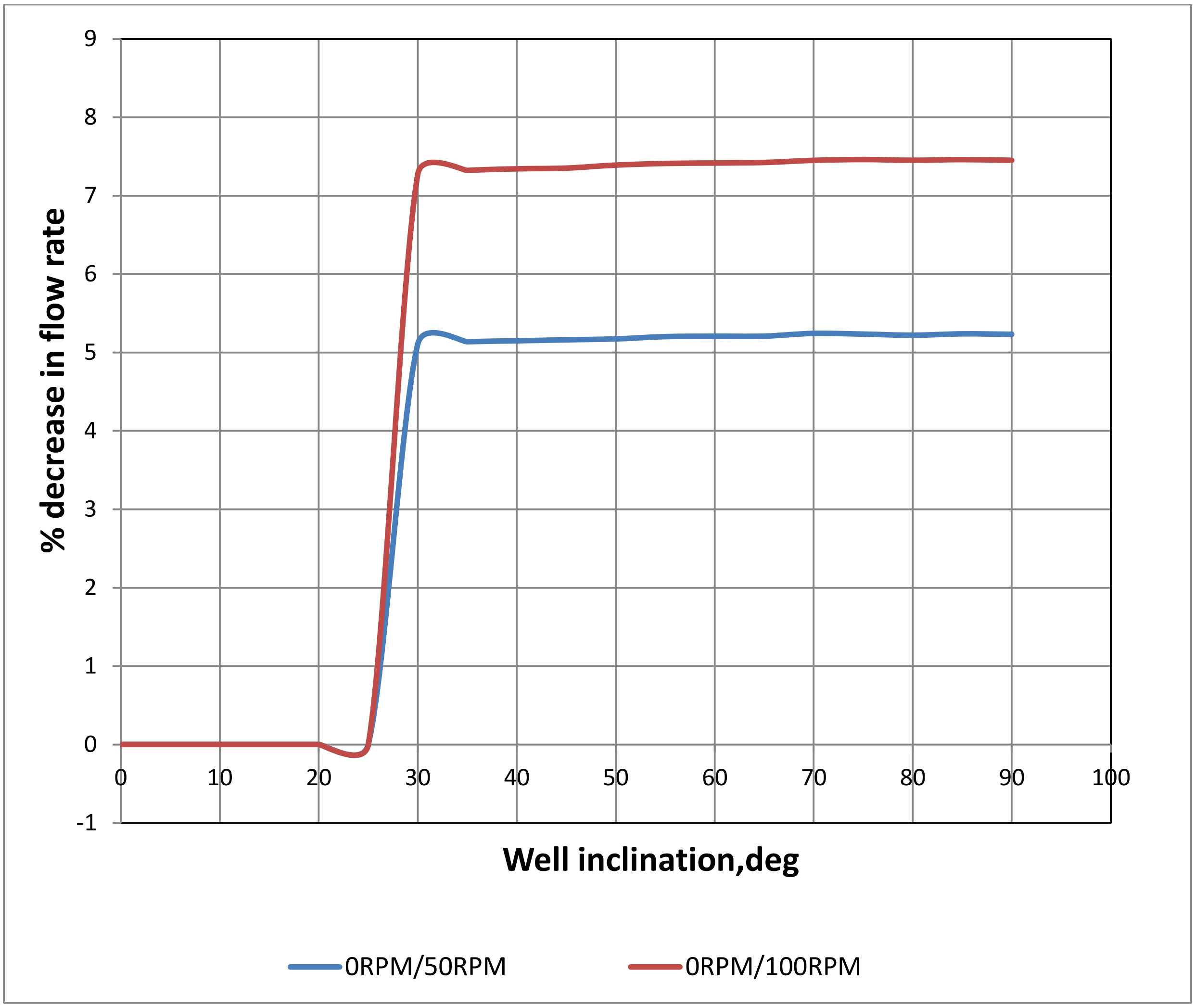


Figure 4.10: % Relative change between RPM effects on hole-cleaning

4.5.4 Drilling fluid density and Rheological property effects

In this section, a simulation study will be presented. The study will investigate the effect of rheology and density of fluid systems. In order to eliminate other effect such as cutting properties and operational parameter, they were kept constant.

4.5.4.1 Effect of Plastic viscosity and Yield stress

In this thesis work a simulation study was performed on the three mud systems (A, B & C) shown in Table 4.3. An attempt was made to generate three relatively closer PV/YS values. For the considered mud systems, the parameters were kept constant, but the Q600 values varied by 3 in order to obtain the desired PV/YS variation. The well size and the drill string is 8.5’’x5’’. The flow rate was considered higher so that the cuttings are completely removed. In this relatively narrower annulus, the flow pattern could be turbulent. The reason for this assumption is that the result obtained from the simulation shows very insignificant difference between the three mud systems. The density and size of cuttings were 2.5sg and 0.125in respectively. The rotatory speed and rate of penetration were 90RPM and 60ft/hr respectively.

Measured Parameters	**Mud A**	**Mud B**	**Mud c**
Q600	73	76	79
Q300	46	46	46
Q200	40	40	40
Q100	26	26	26
Q6	11	11	11
Q3	10	10	10
Density	12.5	12,5	12,5
Calculated parameters			
YS	19	16	13
PV	27	30	33
PV/YS ratio	1,42	1,88	2,54
YS/PV ratio	0.70	0.53	0.39

Table 4.3: Water based mud systems considered for PV/YS ratio effect simulation

Figure 4.11 shows the simulation result. As can be seen as the PV/YS increase, the flow rate required to clean the cutting out of the hole also shows increasing. However, as discussed earlier the effect within the given parameter shows insignificant. In horizontal well, the %

change reaching to about 1.3 %. It should be remember that the observation and analysis is based on the given system.

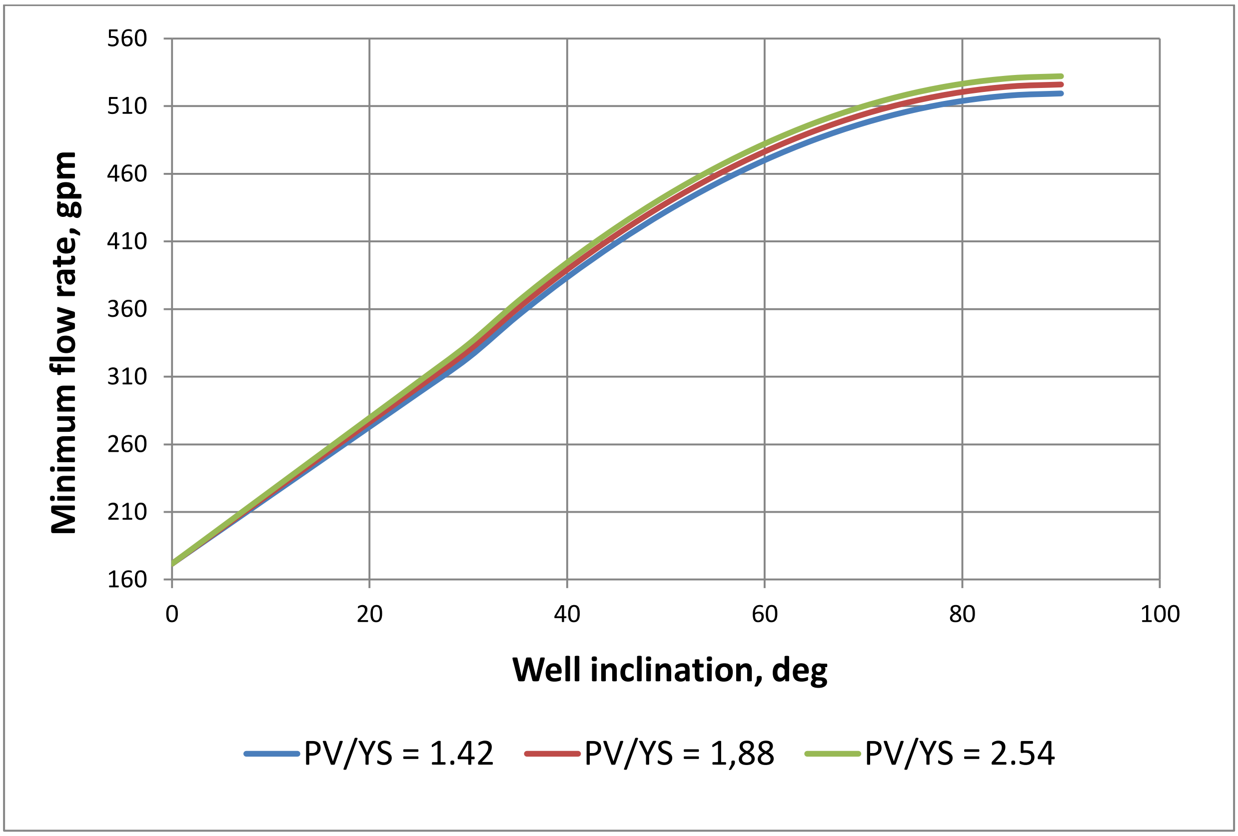


Figure 4.11: Effect of PV/YS on cutting transport

4.5.4.2 Effect of fluid density

For the effect of fluid density on cutting transport phenomenon, three drilling fluid densities were considered. These are 8.5, 10.5 and 12.5 ppg. The rheology of the mud systems were kept constant. The yield stress (YS or YP) =2.54LB/100sq ft, and PV = 17.52cP. The drilling speed was at the rate of 50ft/hr and the drill string rotation was 50RPM. The cutting density and size were 0.25in and 2.145sg respectively.

Figure 4.12 shows the result of the simulation. The fluid weight is seen to have a significant effect on transport. As can be seen, comparing the lower density mud (8.5ppg), the higher the density mud (12.5ppg) moves the cuttings at lower flow rate in horizontal well. One can observer at higher deviated and horizontal angle, the three mud systems shows a higher difference than at the near vertical angle. However, it also shows that in vertical well the three mud systems show almost equivalent performances.

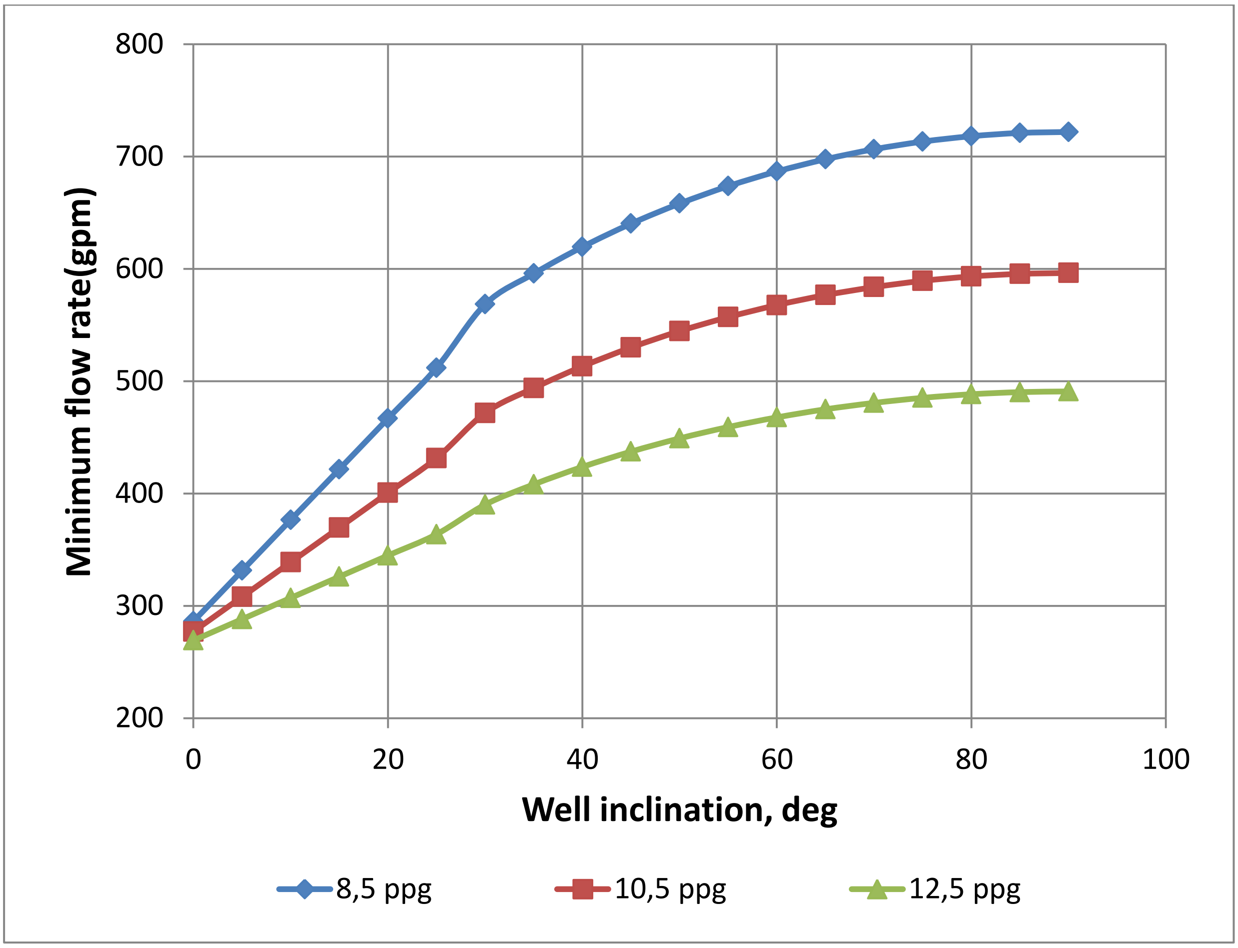


Figure 4.12: Effect of mud weight on cutting transport phenomenon.

Figure 4.13 shows the analysis of the simulation result presented in Figure 4.12. As shown on Figure 4.13, increasing the mud density from 8,5ppg to 10,5 ppg up to 16 % reduction can be achieved for well inclination larger than 40 deg. The % of increment doubles when the density increases from 8,5ppg to 12,5 ppg. The % reduction increases at moderate gradient and comes to the peak at 30 deg and then levels out irrespective of well inclination.

In this study, it was found out that fluid with higher density performs better than fluid with lower density. As clearly shown on Figure 4.12, the performance of denser fluid is substantial as well inclination increases by decreasing the flow rate. Larsen (1990) [5] in his studies concluded that for a given viscosity, higher mud density would improve cutting transport performance.

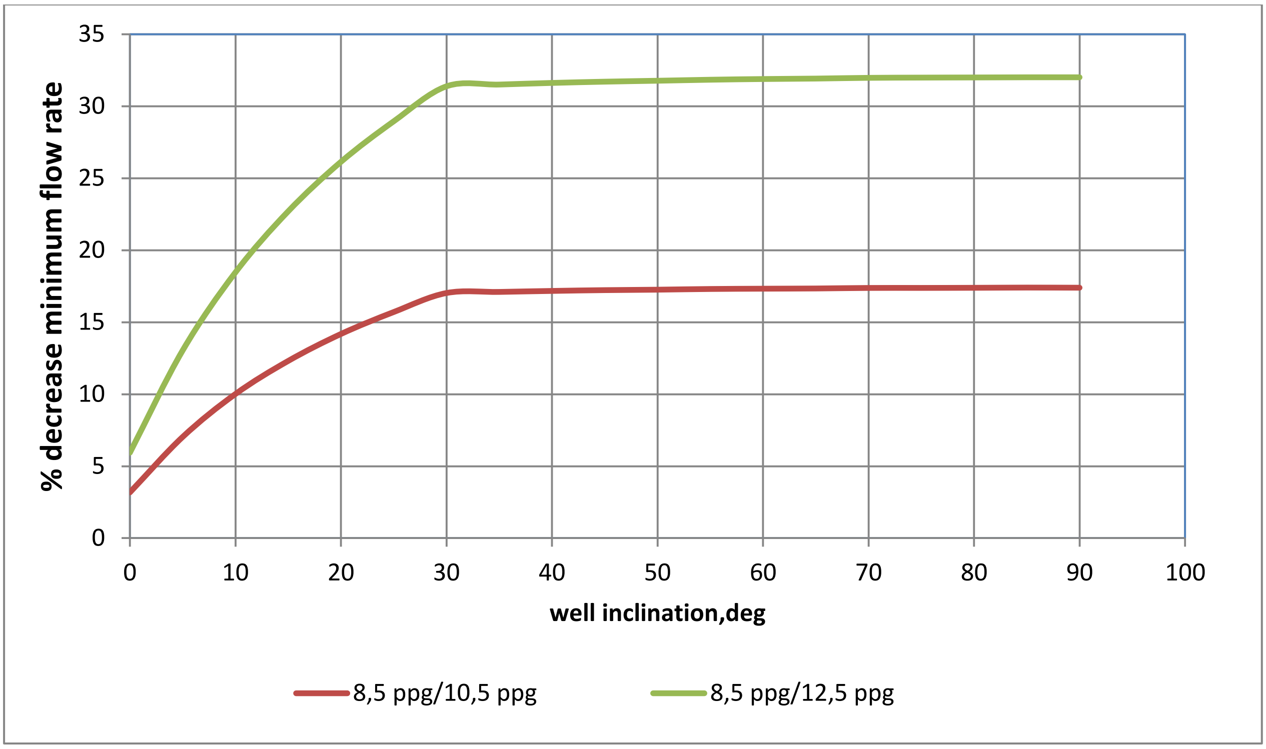


Figure 4.13: % Relative change between mud densities analysis

4.5.5 Cutting property effects

4.5.5.1 Effect of cutting density

For this simulation, two types of mud systems were considered as show in Table 4.4. The operational parameters and the cutting properties are kept constant throughout the simulation. The main objective here was to study the sensitivity of cutting density in the given two mud systems.

	Q600	Q300	Q200	Q100	Q6	Q3	Gel 10sec/10min Lbf/100sqft	PV cP	YS (YP) Lbf/100sqft	Density Pcf
Mud 2	10	6	4.5	3.6	1.5	1	2.53/3	5	1	68
Mud 3	76	46	40	26	11	10	4/5	27	19	69

Table 4.4: Rheology measured data of water based systems Mud 2 and Mud 3

The density of cutting was chosen from typical log properties. Coal (1.2- 1.5 g/cc), poorly consolidated shale (2-2.8 g/cc), carbonate with 10% porosity (2.56 g/cc), Sandstone (2.65 g/cc) and Carbonate 2.71 g/cc, Ingenious (2.9 g/cc). The well/bit size is 10.625 in. For all the simulation the cutting size was 0.125in. The rotary speed was 90rpm and the rate of penetration is 60ft/hr.

Simulation result with mud system #2 (lower viscous)

Figure 4.14 shows the simulation result for various cutting density. The result shows that the lower cutting density is easier to clean out from the well. As the well inclination increase the flow rate also increase.

Simulation with mud system #3 (higher viscous)

Figure 4.15 shows the simulation result in a relatively higher viscous mud system. As can be observed from the less viscous and higher viscous fluid systems, as cutting density increase, higher flow rate require to clean the cutting out of the hole. Figure 4.16 compares the heavier (igneous=2.9sg) and the lighter (Coal=1.13 sg) cutting transport behavior. It is interesting to observe a different phenomenon. As shown on the figure, for the heavier cutting (igneous), as the viscosity increase the flow rate also shows even at a higher difference (350gpm) in horizontal well. One can also observe that the lighter cutting required a lower flow rate in the viscous mud system as compared in lower viscous fluid system. However, the difference is insignificant.

For better visualization and analysis, Figure 4.17 shows the difference between the simulation results obtained from mud 3 (i.e Figure 4.14) and mud #2 (i.e Figure 4.15). As can be see, the heavier cutting shows higher flow rate in both mud systems, whereas the lighter cutting density (eg. Unconsolidated and coal) shows good hole-cleaning performance in less viscous mud system. An attempt was made to review if this simulation result confirms with small scale laboratory results documented in literature and we ended up without success. However, interested readers may do experiment to verify the simulation result.

Figure 4.16 shows the cleaning behavior of lighter and heavier cuttings in less viscous and relatively higher viscous mud systems.

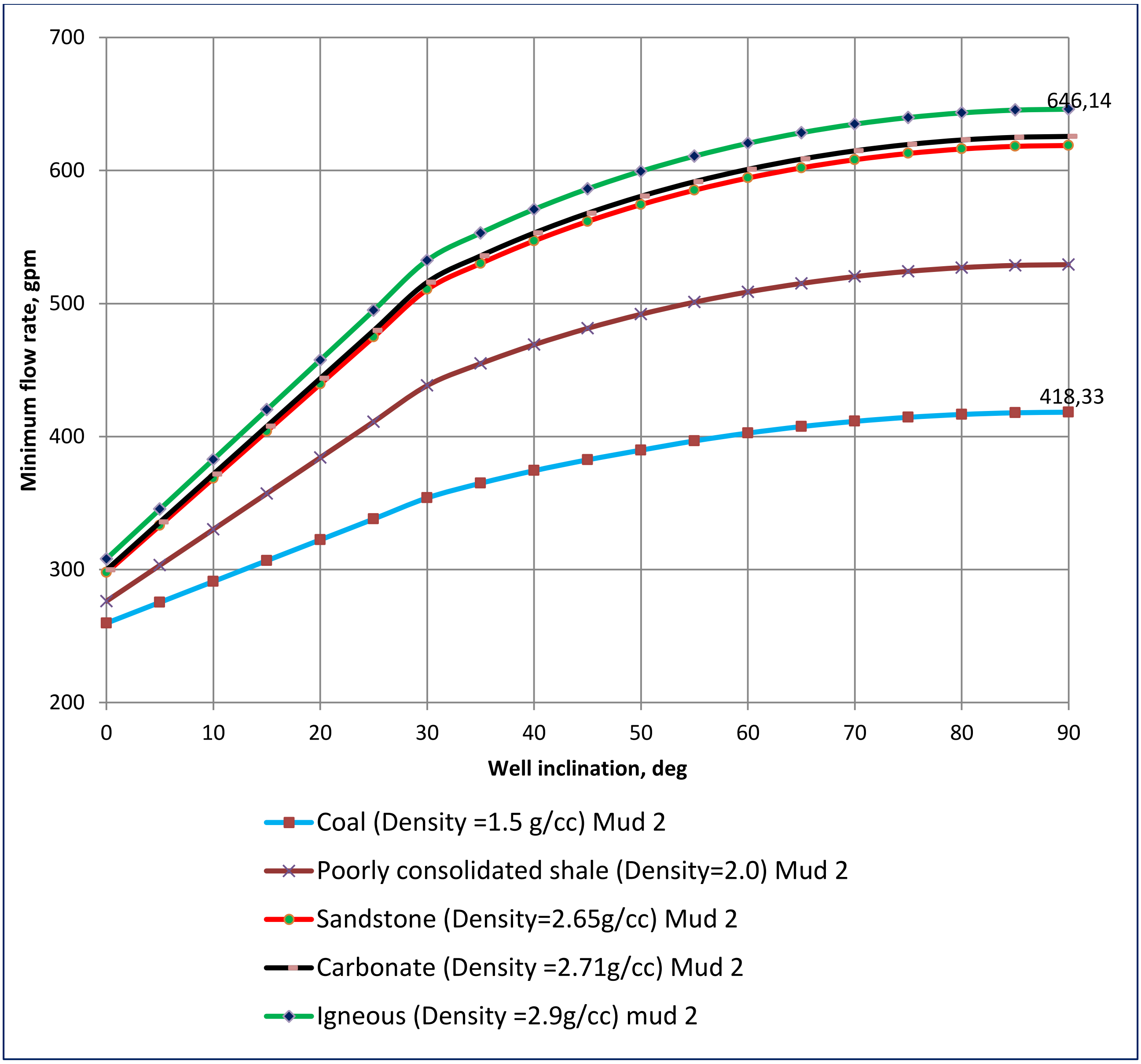


Figure 4.14: Effect of cutting density on hole cleaning in less viscous mud system Mud #2

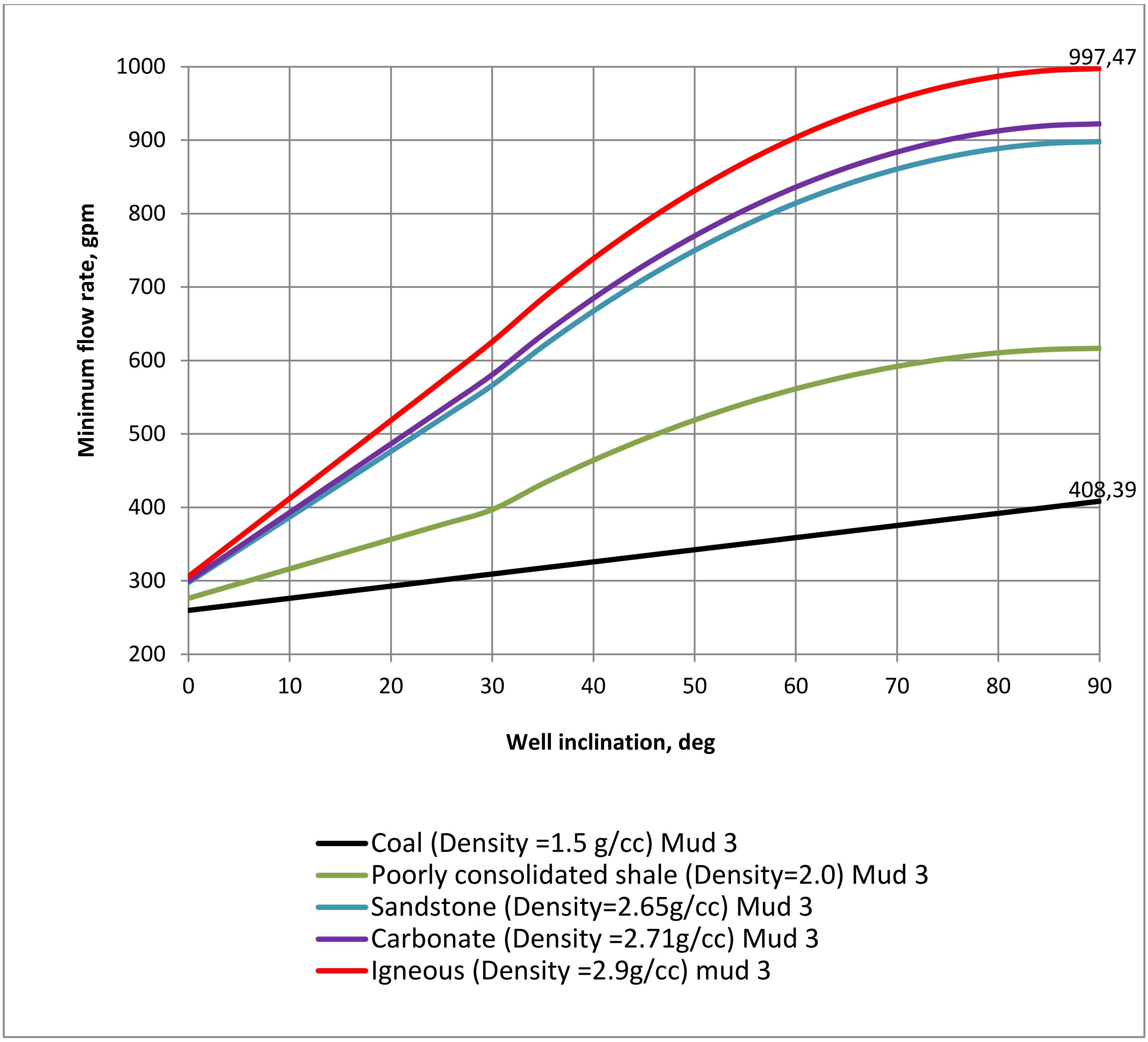


Figure 4.15: Effect of cutting density on hole-cleaning in viscous mud system Mud #3

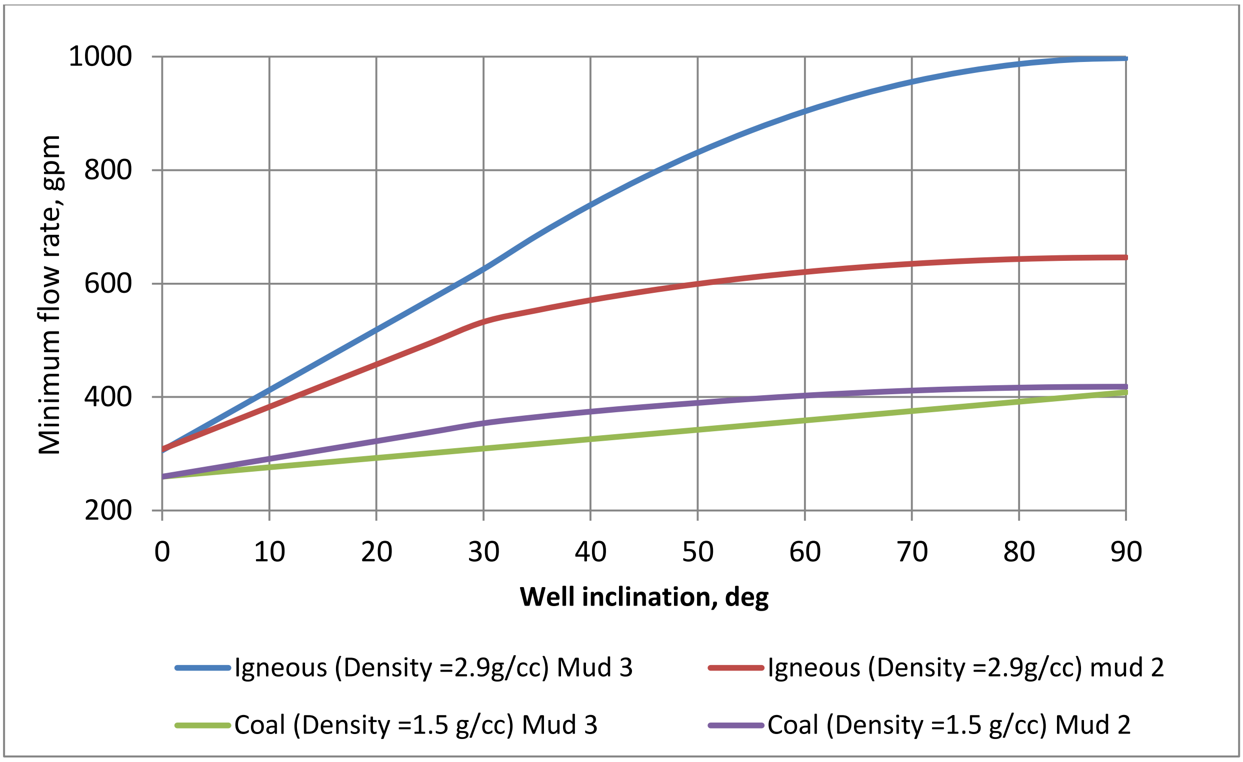


Figure 4.16: Comparison of heavy and light cutting in viscous and less viscous mud systems

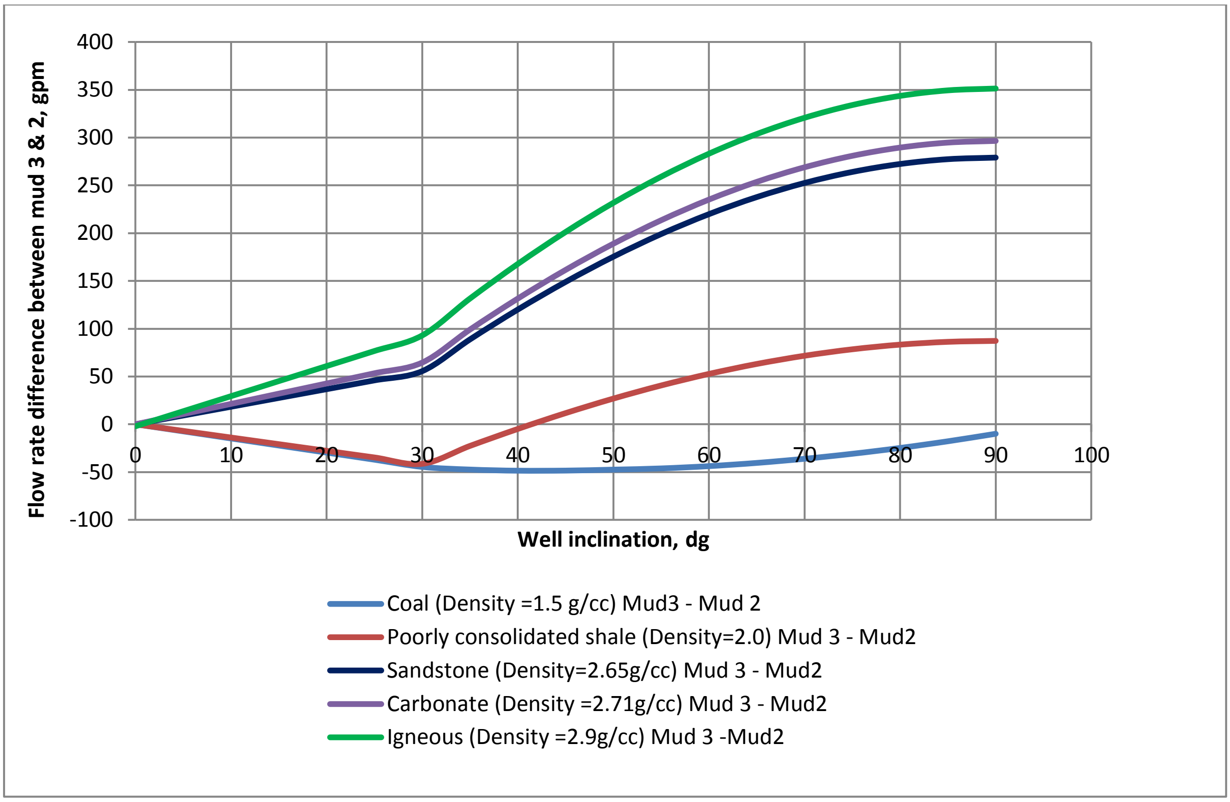


Figure 4.17: Difference flow rates between of cuttings in viscous and less viscous mud systems

4.5.5.2 Effect of cutting size

Cutting size is one of the parameter that influences the hole-cleaning phenomenon. For this simulation the small, medium and large sized cuttings were considered for the analysis. Figure 4.18 shows the simulation result.

The result shows that for the range of well inclination up to approximately 30 deg from vertical, the three cutting sizes transport behaves similar. However, for the larger size, more flow rate is required to clean the hole.

In general larger size and heavier cutting makes the hole cleaning more difficult and require higher pump rates for high-viscosity fluids.

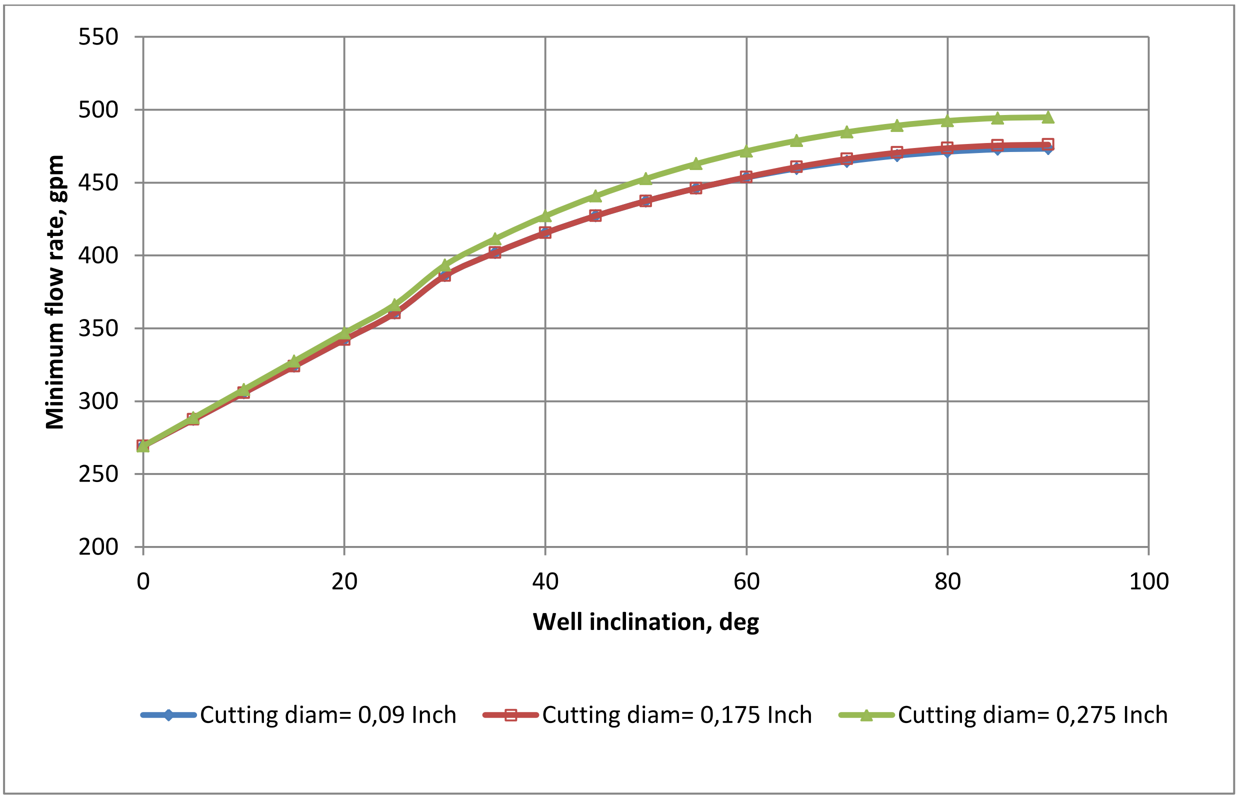


Figure 4.18: Effect of cutting size on hole-cleaning

As indicated on Figure 4.18, the impact of cutting size on flow rate is not substantial. Figure 4.19 shows the analysis of simulation result. When the cutting size increases from 0.09 inch to 0.275 inch the flow rate increases to 4,5 % at higher angles from vertical. In the case of increasing the cutting size from 0.09 inch to 0,175 inch, there is no change in flow rate up to 60 deg. After an inclination of 60 deg a very minor increase in flow rate takes which is less than 1 %. In general, altering cutting size alone does not have significant role in enhancing hole-cleaning**.**

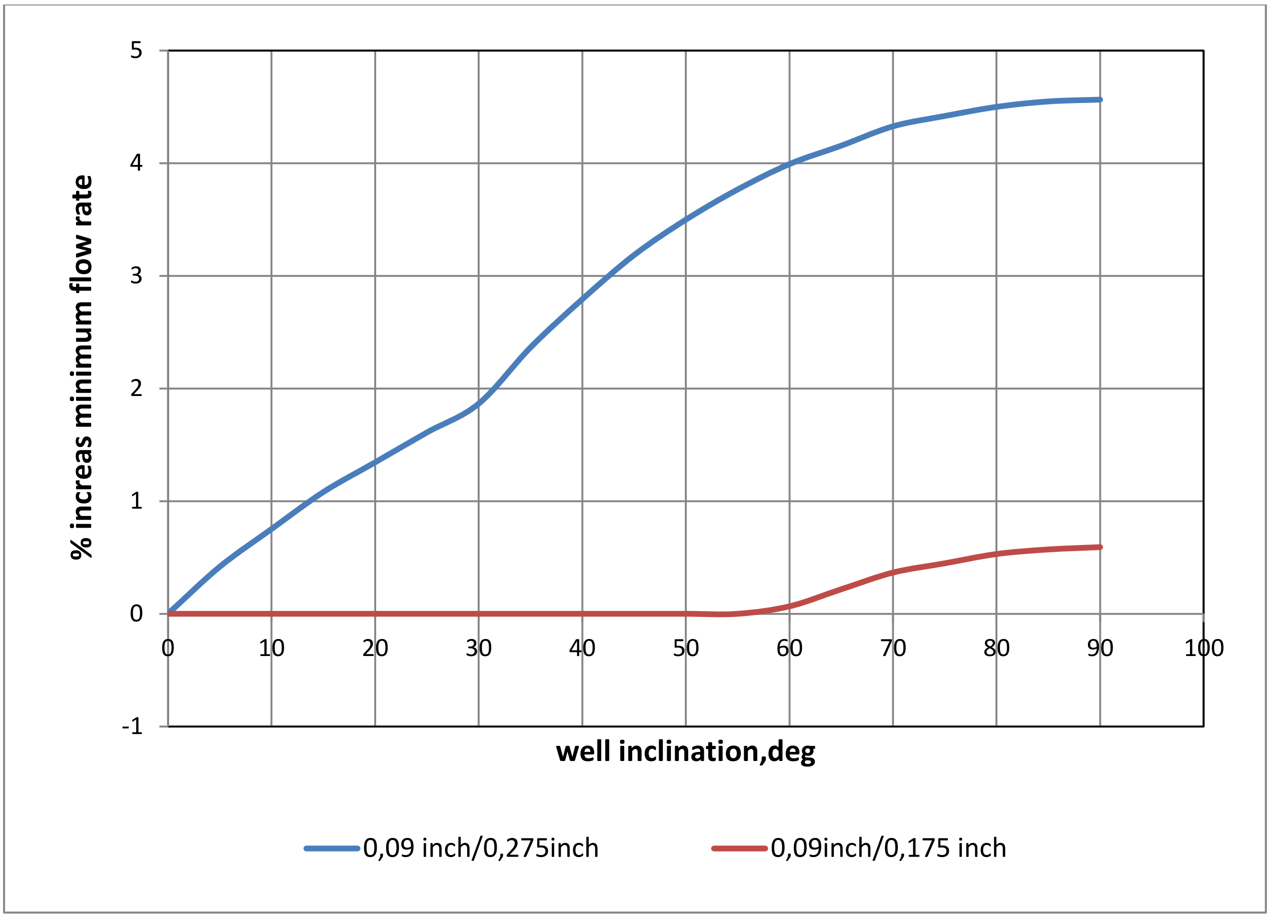


Figure 4.19: Analysis of % change in cutting size effect on hole-cleaning

4.5.6 Effect of annular size and well length

4.5.6.1 Effect of annular size

The effect of annular size on the cutting transport phenomenon was studied by considering three well sizes. These are 8.5in, 10.5in and 12.5in. For the investigation the mud system 2 was considered. For the simulation, the cutting diameter was 0.12, and density was 2,5g/cc. The rate of penetration and the rotary speed were 62.5ft/hr and 100rpm respectively.

As the borehole size increase, the concentration of cutting excavated per a given period of time would be higher. The simulation result is shown in Figure 4.29. As can be shown as the well size, the higher flow rate required to clean cutting effectively. One can also observe that the difference in flow rate between the 8.5 & 12in hole sizes higher in horizontal well (i.e. 443 gpm) than the vertical well (243gpm).

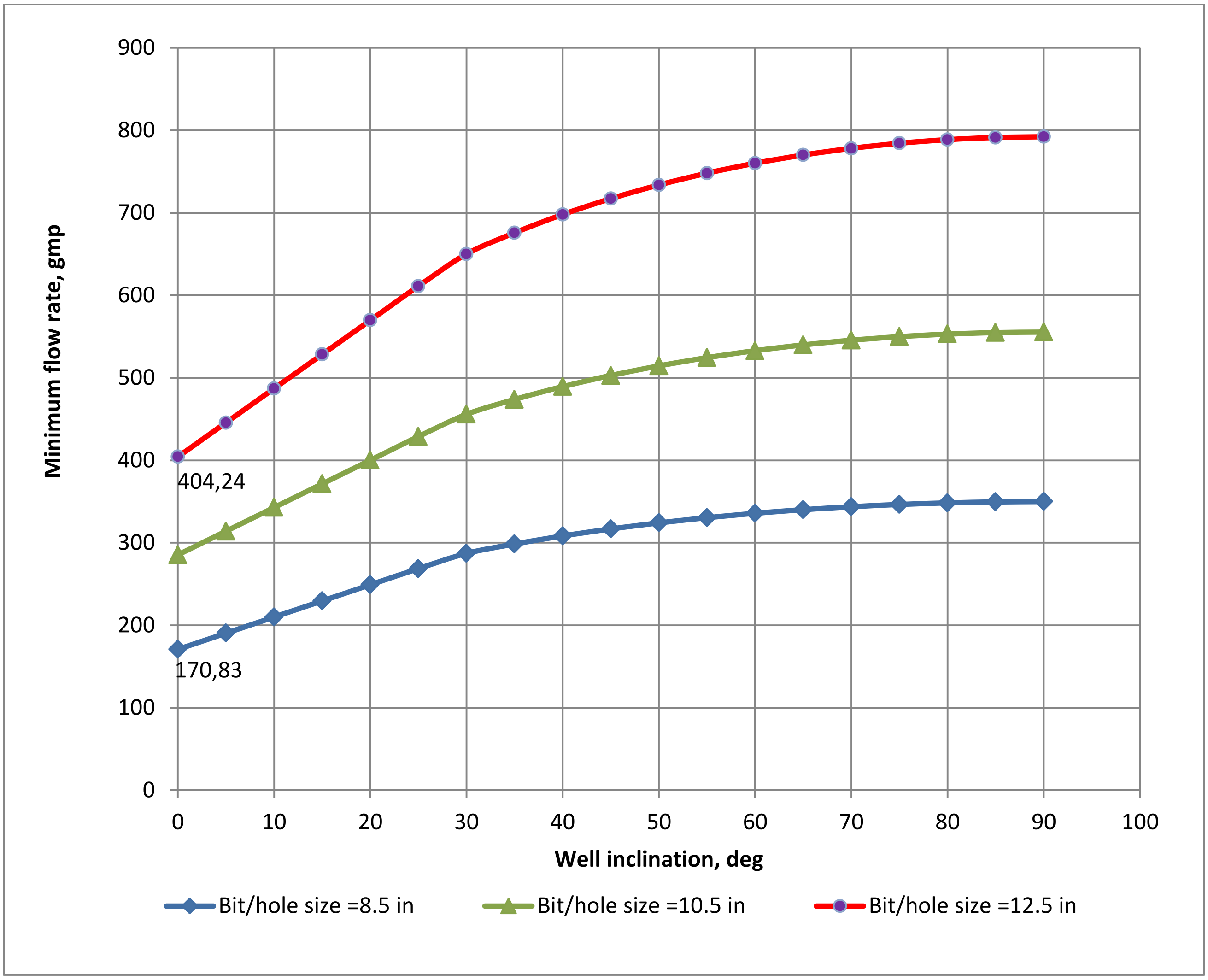


Figure 4.20: Sensitivity of well size on cutting transport

From the simulation (Figure 4.20), it is evident that demand for flow rate is very sensitive to changes in the size of the hole. Figure 4.21 shows the analysis of the simulation result presented in Figure 4.20. When the hole size increases from 8. 5 inch in diameter to 10.5 inch, the % increase in flow rate is around 60 % for near vertical inclinations. For inclinations larger than 35 deg, the % increase becomes constant at around 58 %. The % increase double - folded the above mentioned when the hole-size increases from 8.5 inch to 12.5 inch. The inclination of the hole does not have so much impact for intermediate and larger angles from the vertical. Over all, the smallest increase in the size leads to larger demand in flow rate. This may be due to additional cutting volume added to the annulus as a result of increased diameter.

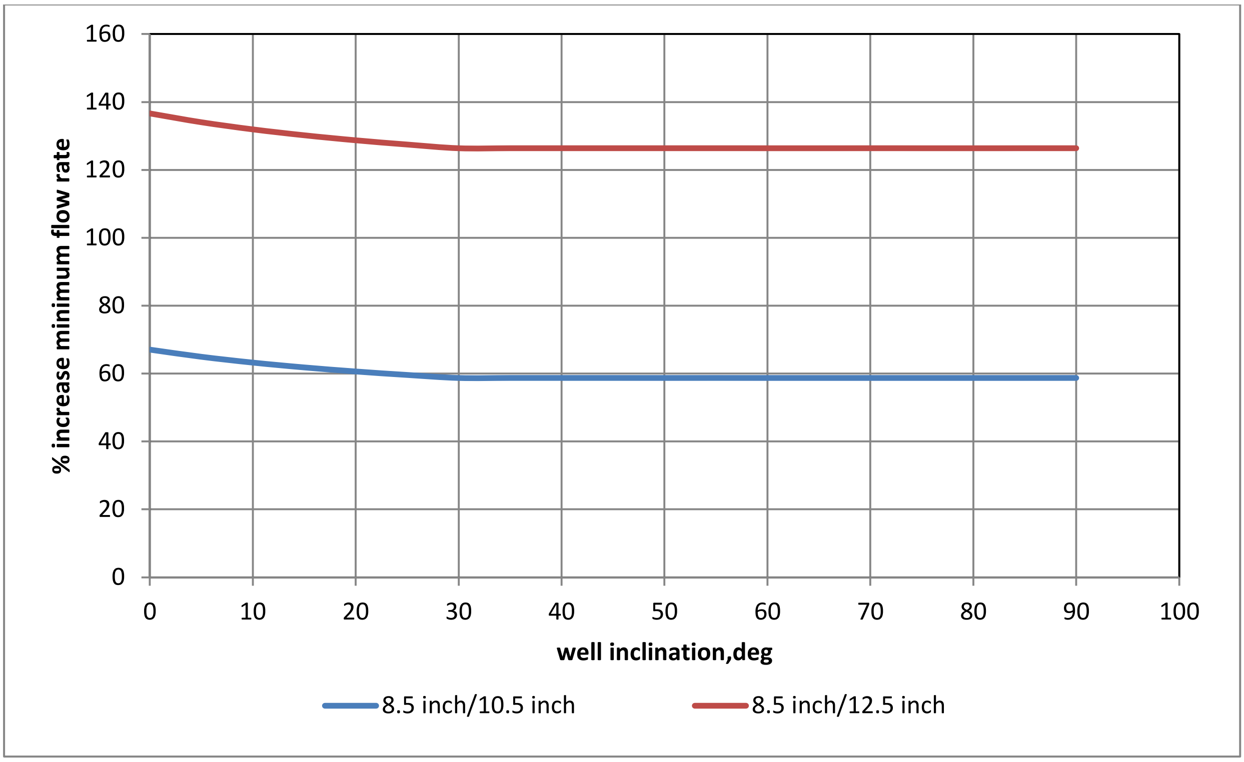


Figure 4.21: Analysis of % change in flow rate due to change in hole size

4.5.6.2 Effect of well length

The sensitivity of well length on cutting transport is simulated. For the analysis the rheology of Mud 3 was considered. The rate of penetration and the rotational speed was 60ft/hr and 90RPM. The well size is 12.625in and the bit size is 10.625in.

	Q600	Q300	Q200	Q100	Q6	Q3	PV cP	Gel 10sec/10min Lbf/100sqft	YS lbf/100sqft	Density pcf
Mud 3	76	46	40	26	11	10	27	4/5	19	69

Table 4.5: Rheology measured data of water based mud system

Two well lengths were considered, namely measured depth, MD=1003ft and MD=11003ft. It is well known that the pressure loss in the longer well length is higher. During cutting transport simulation, the size of cuttings used was 0.0625in, 0.125in, 0.25in, 0.275in and 0.30in. The simulation results shows that the results obtained from 0.0625 to 0.025in are almost the same. The cutting size responds at higher angle when the cutting size increased to 0.275in. Therefore the simulation results presented are for cutting sizes 0.25 in, 0.275 and 0.30in (Table 4.6). The main reason for the similar observation is that the cutting transport model is not a function of the well length.

Hole Angle(°)	MD =11003ft & Cut Diam =0.3in	MD =1003ft & Cut Diam = 0.30in	MD =11003ft & Cut Diam = 0.275in	MD =1003ft & Cut Diam = 0.275in	MD =11003ft & Cut Diam=0.25in	MD = 1003ft & Cut Diam = 0.25in
0	413	413	413	413	413	413
5	461	461	461	461	461	461
10	509	509	509	509	509	509
15	557	557	557	557	557	557
20	605	605	605	605	605	605
25	653	653	653	653	653	653
30	702	702	702	702	702	702
35	772	772	772	772	772	772
40	836	836	836	836	836	836
45	894	894	894	894	894	894
50	953	953	946	946	946	946
55	1008	1008	992	992	992	992
60	1056	1056	1036	1036	1033	1033
65	1096	1096	1076	1076	1067	1067
70	1130	1130	1109	1109	1095	1095
75	1157	1157	1135	1135	1117	1117
80	1176	1176	1154	1154	1132	1132
85	1187	1187	1165	1165	1142	1142
90	1191	1191	1169	1169	1145	1145

Table 4.6: Effect of well length on cutting transport model

4.5.7 Effect of flow rate on cutting bed deposition

The simulation results presented in the previous sections deals with the determination of minimum flow rate to completely clean cuttings out of the hole without bed formation. In this section an attempt is made to study the sensitivity of flow rate on cutting bed deposition when the flow rate is lower than the minimum flow rate. The study will look into the situations at various angles. The operational parameters used for this simulation were ROP 50ft/hr and rotations speed of 50RPM.The cutting density and cutting size were 2.65 & 0.250 respectively. The 12.5ppg density of the mud density was used as transport media.

Figure 4.22 shows the simulation result. As can be seen on the Figure, the 625gpm flow rate is the minimum flow rate that capable of completely cleaning the cutting out of the hole throughout the drilling depth. However, when the flow rate reduces from the minimum flow rate the cutting beds begin forming in highly to lower well inclination. This simulation illustrates the demand for minimum flow rate to clean the hole increases with inclination. The formation of cutting bed correlates to the flow rate in that when the flow rate is less than the minimum requirement, particles begin to settle and form bed in the annulus. For this simulation we need to start to operate with 475 gpm up to 20 deg, then increase the rate to

525 gpm and use it up to 40 deg. Then use 575 gpm to 60 deg inclination. Above 60 deg, 625 gpm is the minimum requirement to get the hole cleaned.

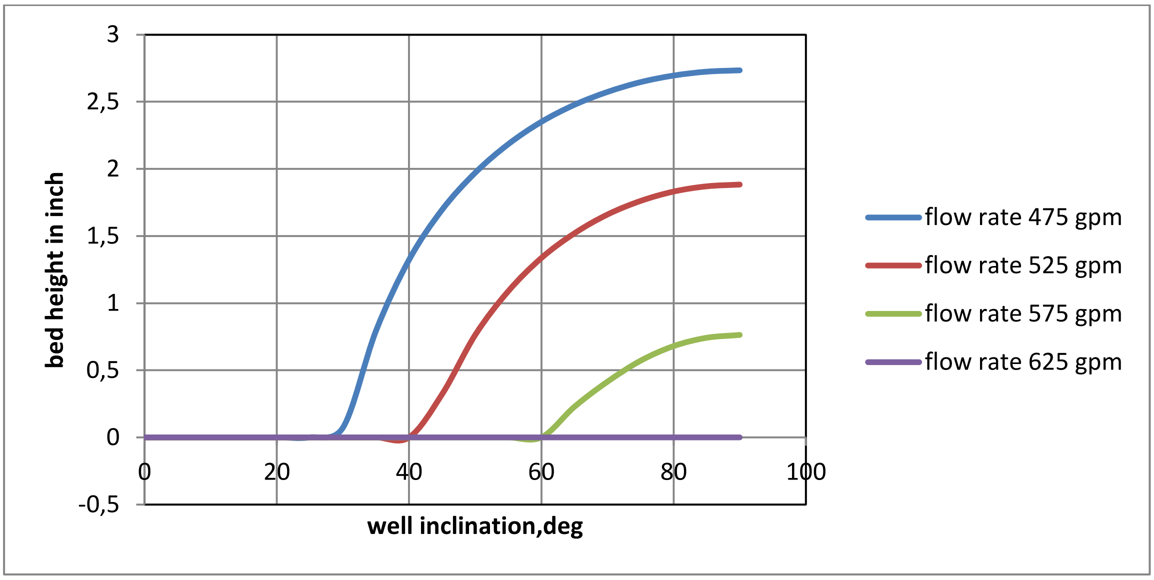


Figure 4.22: Sensitivity of flow rate with respect to cutting bed formation

4.5.8 Parameters combined effect on cutting transport

For the investigation, three water based mud drilling fluids were considered. Table 4.7 shows viscosity parameters.

Measured parameters	Mud 1	Mud 2	Mud 3
Q600	10	37	73
Q300	6	20	46
Q200	4,5	15	40
Q100	3,6	9	26
Q6	1,5	2,5	11
3	1	1,5	10
10 Sec -Gel (lbf/100sq ft)	2,53	2	4
10 min -Gel (lbf/100sq ft)	3	2,5	5
Density, pcf	68	64	69

Based on the given mud system, the simulator computes the viscosities as the following

Mud 1	**Mud 2**	**Mud 3**
PV=4.34 cP	PV=17.52cP	PV=31.3cP
YP=1.61 lb/100sqft	YP=2.54 lb/100sqft	YP=14.15lb/100sqft

Table 4.7: Water based mud systems used for combined effect investigation

The comparisons are between mud 1/2 and mud 2 / 3 which is:

1. PV (4.34/17.52) & YP(1.61/2.54)
2. PV (17.52/31.3) & YP(3/14.15)

As can be seen PV = 13.18 and 13.78 are nearly equal, but the difference between YP is relatively very high. In the following section the relative difference of the cutting transport velocity of between mud systems 1& 2 and 2 & 3 are compared.

4.5.8.1 Combined effect of viscosity and RPM

The simulation was conducted by using the three different mud types mentioned above. Two pipe rotations; 50RPM and 100 RPM were used. The rate of penetration (ROP) was 50ft/hr. Cutting size and cutting density were 0.275 in. and 2,145 sg respectively. The purpose of the simulation was to find out what impact does the variation of the two parameters have on minimum flow rate.

As shown on Figure 4.23 below, the minimum flow rates for mud 1 and mud 2 are very close to one another irrespective of the pipe rotation. The minimum flow rate for mud 3 strongly deviates from the two other mud systems after an inclination of 30 deg. The impact of rotation (50 & 100 RPM) is not visible for mud 1 & mud 2, since the curves for 50 & 100 RPM are almost overlapping. In case of mud 3 there is slight variation for the two pipe rotations (50& 100 RPM).

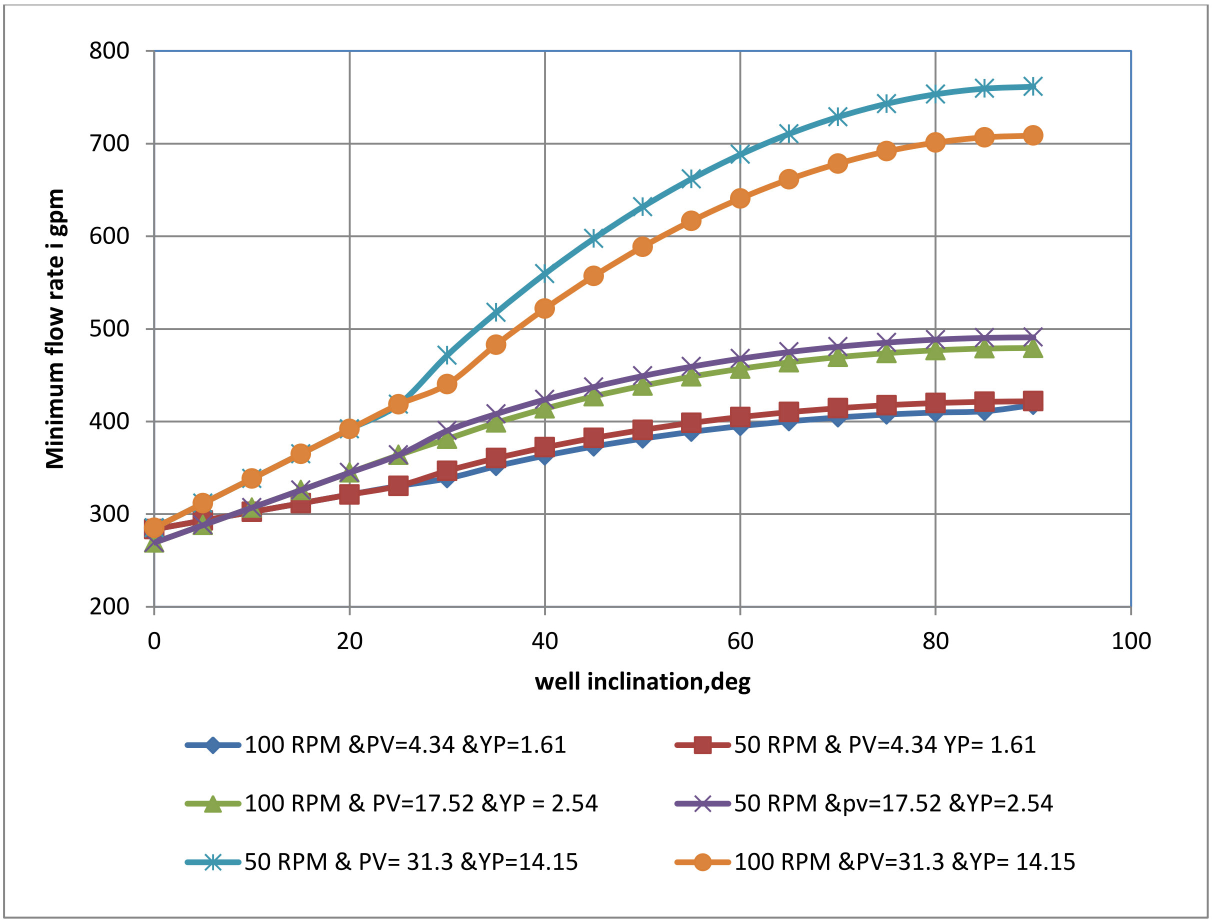


Figure 4.23: Combined effect of rotary speed & rheological properties

Figure 4.24 shows the analysis of the effect of RPM between mud systems 1 and 2 and mud systems 2 &3. The result shows that as RPM increase from 50 to 100, the % increase in minimum flow rate reaches to about 16% in the lower yield stress mud system.

The effect in the higher yield stress mud systems, the % increase reaches to 55% and 48% for RPM 50 and 100 respectively. The combined effect of the parameters is very significant as the yield stress (YS) increases from 2.54 to 14.15lbf/100sqft. For muds with higher viscosity the impact of pipe rotation is considerable. By decreasing or increasing the viscosity and yield stress/point of the mud (PV,YP) in combination with the pipe rotation, the flow rate is significantly altered. In mud systems with low yield stress increasing or decreasing the pipe rotation does not have an impact. On the figure, the% increase in flow rate is the result of change in rheological properties (PV and YP).It seems logical to say that the yield stress plays major role in influencing the flow rate requirement to clean the hole. Thus, it is possible to manipulate the yield stress in combination with pipe rotation to reduce the flow rate by altering the plastic viscosity in proportional way.

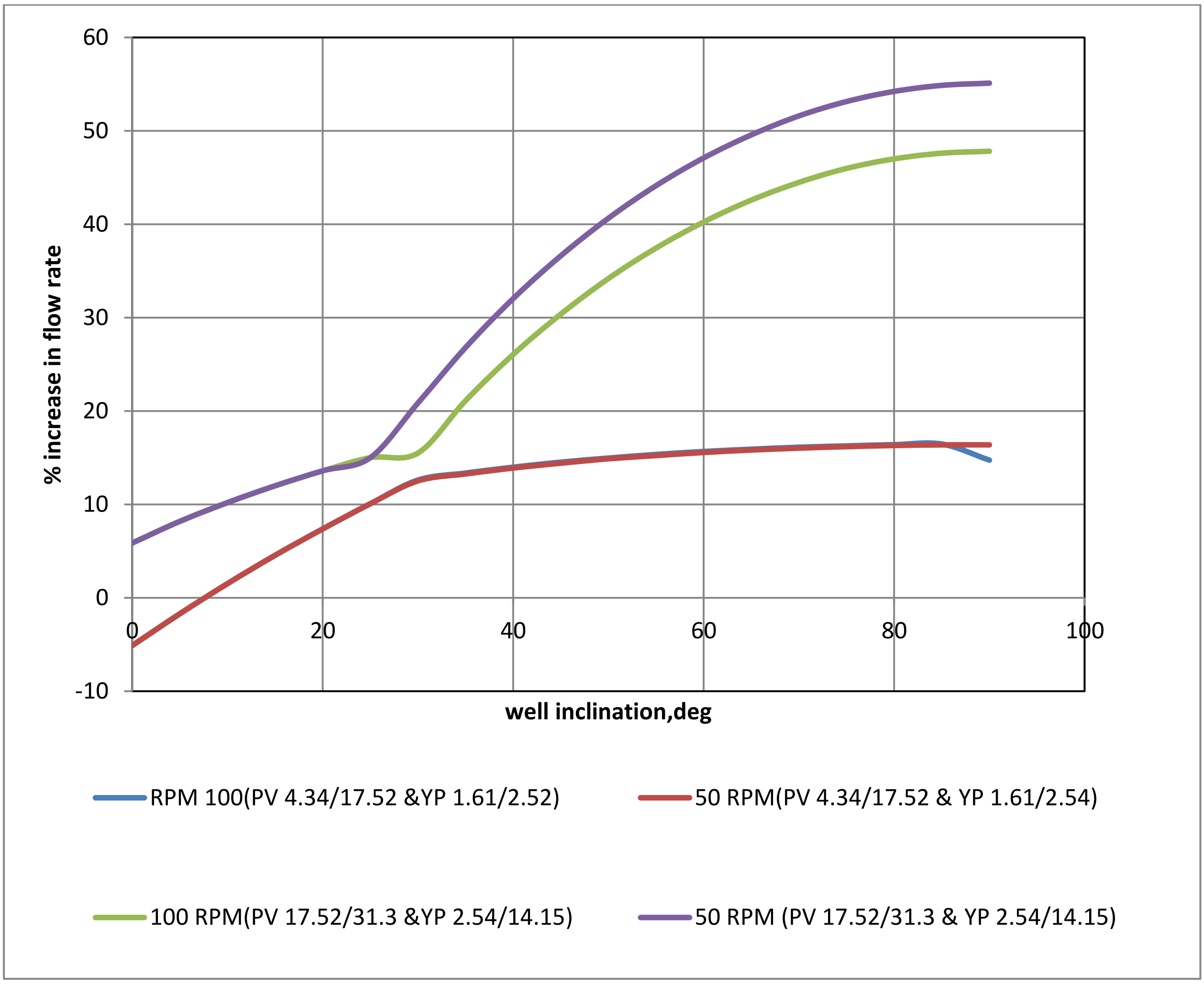


Figure 4.24: % Relative flow rate changes for combined effects in higher and lower viscous mud systems

4.5.8.2 Combined effect of ROP and RPM

In this simulation the two operational parameters, rate of penetration (ROP) and pipe rotation (RPM) were subjected to variations. The cutting size and density used were respectively. The mud used for the simulation was mud 2 mentioned above. The cutting size and destiny and size were 2.145 and 0.250 respectively while the fluid density was 12.5 ppg. As can be seen on figure 4.25 the flow rate is highest for ROP 50 and when the pipe is stationary, while the lowest flow rate is when ROP is 30 and the pipe rotation is 100 RPM. However, once the pipe is in rotation, the flow rate reduction is insignificant even when the rotation speed increases.

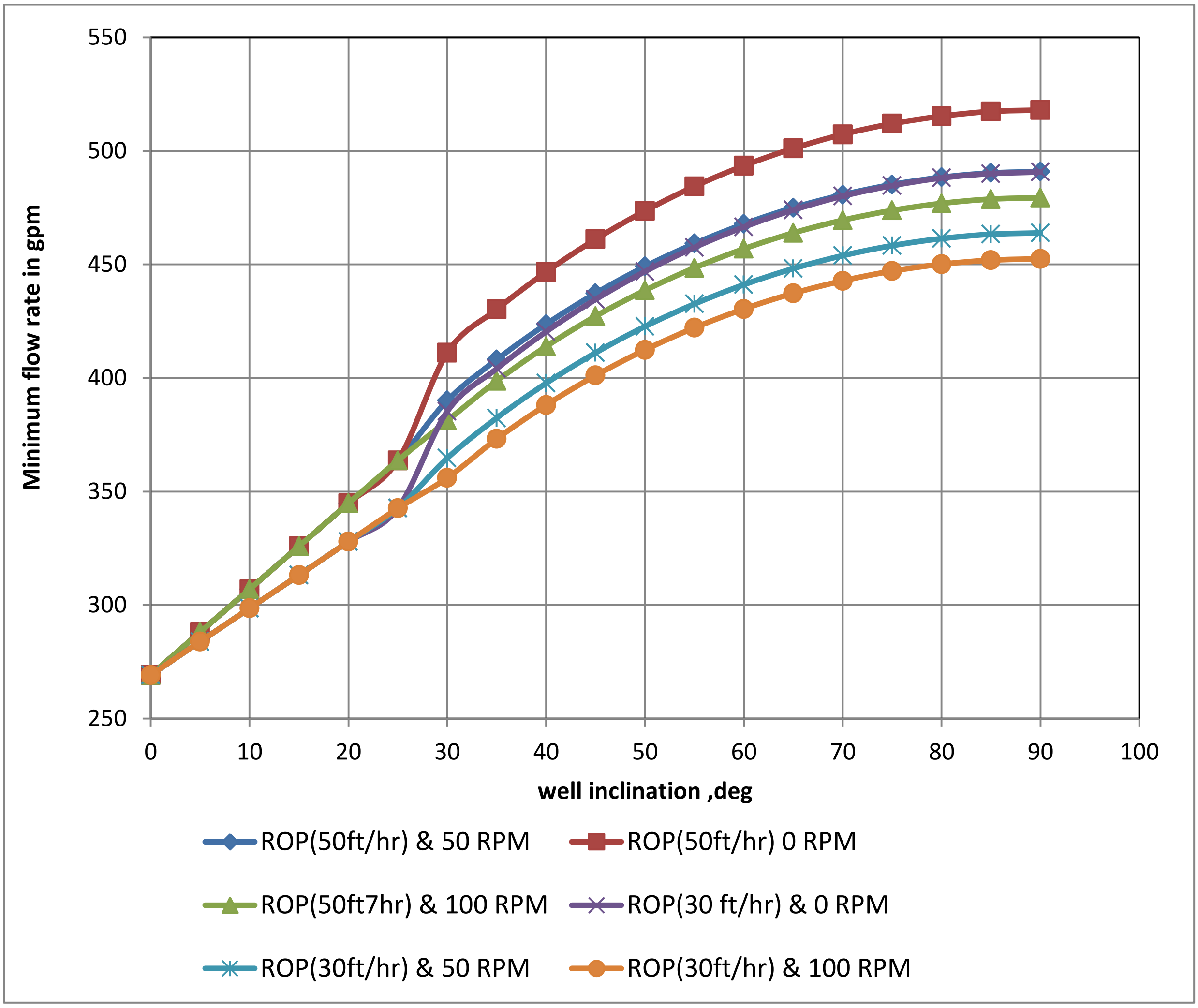


Figure 4.25: Combined effect of ROP and RPM

Figure 4.26 shows the analysis of relative flow rate change due to the combined effects of ROP and RPM presented in Figure 4.25. We can observe the same change in RPM (from 0-50 and 50-100). Under this condition different ROP were used as an input. As can be seen at 30ft/hr ROP, the relative decrease in minimum flow rate is 2.4% and 5.4% as RPM increases from 50/100 and 0/50 respectively. For ROP 50 ft/hr, the % decrease is 2.3% and 5.1% as RPM changes from 50 to 100 and 0 to 50, respectively.

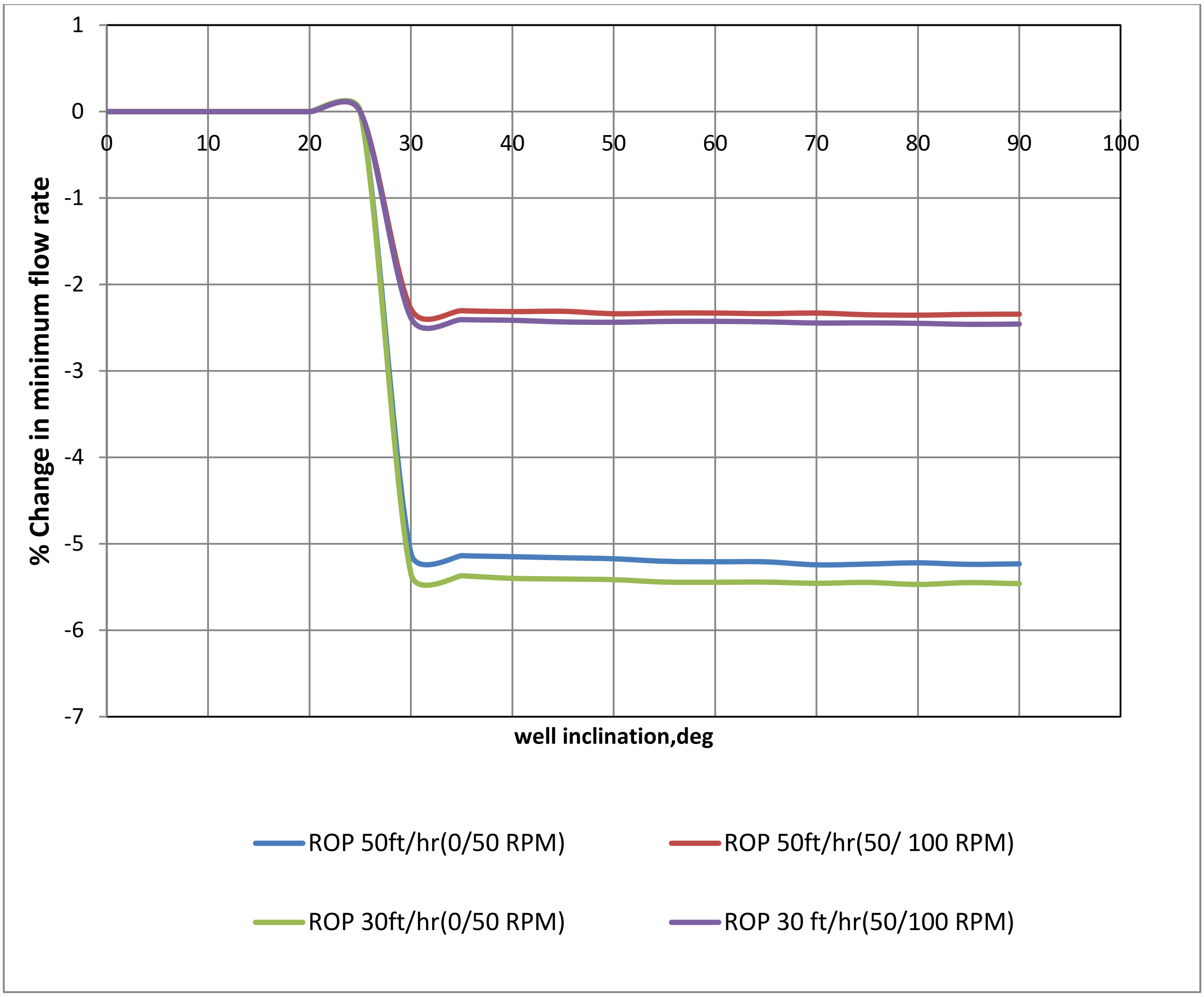


Figure 4.26: % Relative change of flow rate for the RPM and ROP combined effects

4.5.8.3 Combined effect of cutting size and viscosity

The effect of each cutting sizes is compared as the mud system changes from PV =4,31 to 17,52 cP and PV=17,52 to 31,3cP. The simulation was performed at RPM/ROP (50/50).

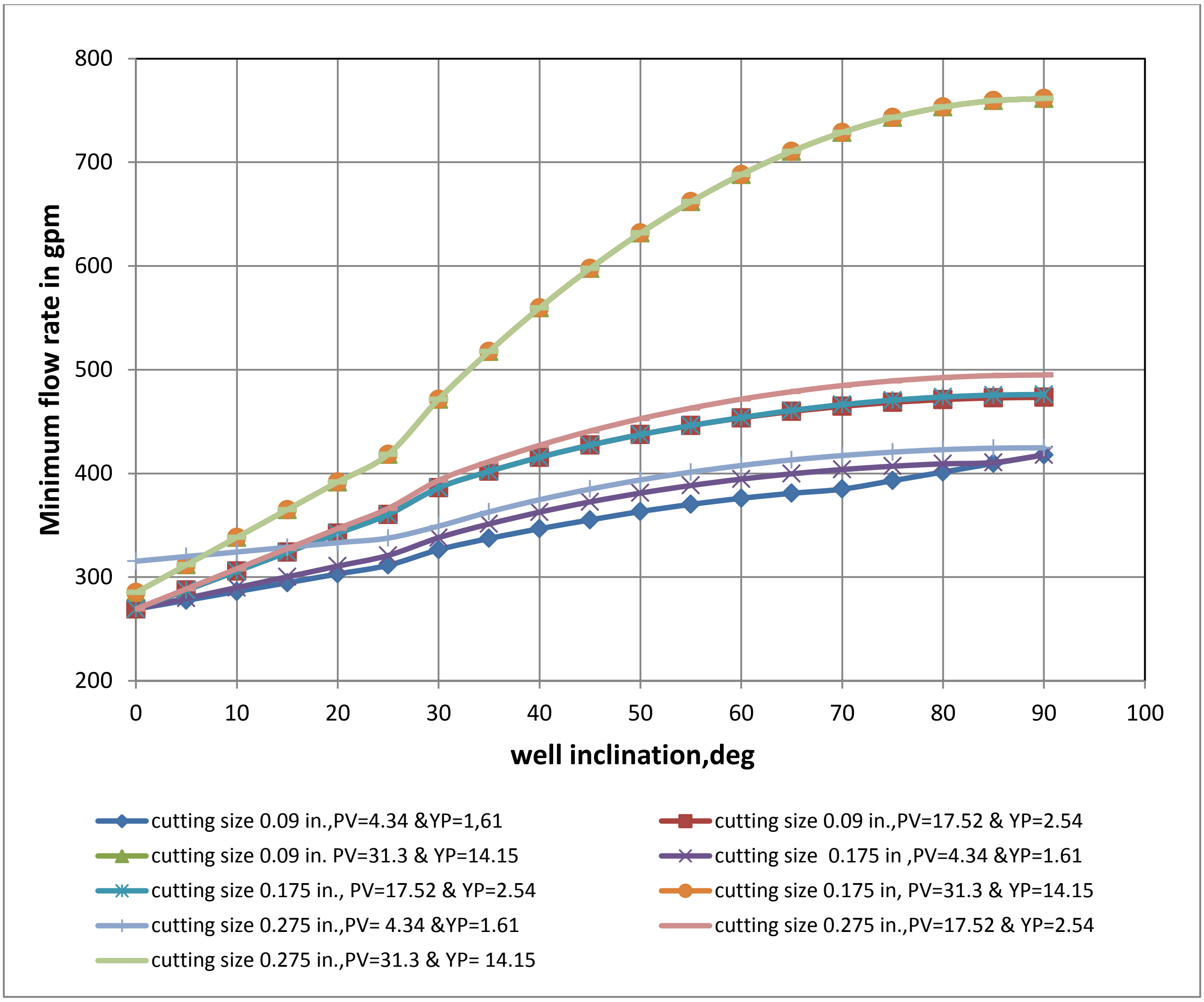


Figure 4.27: Combined effect of cutting size and viscosity and yield stress

As can be on Figure 4.28, the % change increases shows very high in the very high yield stress mud system. We can observe a similar effect as shown in section 4.5.6.1. The minimum flow rate increases when the mud system changes irrespective of the cutting size. In the figures, the trends are similar, with minor variation at higher inclinations. In all the three cutting sizes, the demand for minimum flow rate to clean the hole significantly increases when the yield stress difference is larger. For instance at 60 deg well inclination, for cutting size 0,09inch, when plastic viscosity and yield stress increased from (PV=4.34cP, YP=1lbf/100sqft) to (PV=17.52cp, YP=3 lbf/100sqft), the minimum flow rate increased by 20%. For the same cutting size at 60deg, the flow rate increased by 50 % when plastic viscosity and yield stress increases from (PV=17,YP=3) to (PV=31,YP=19).

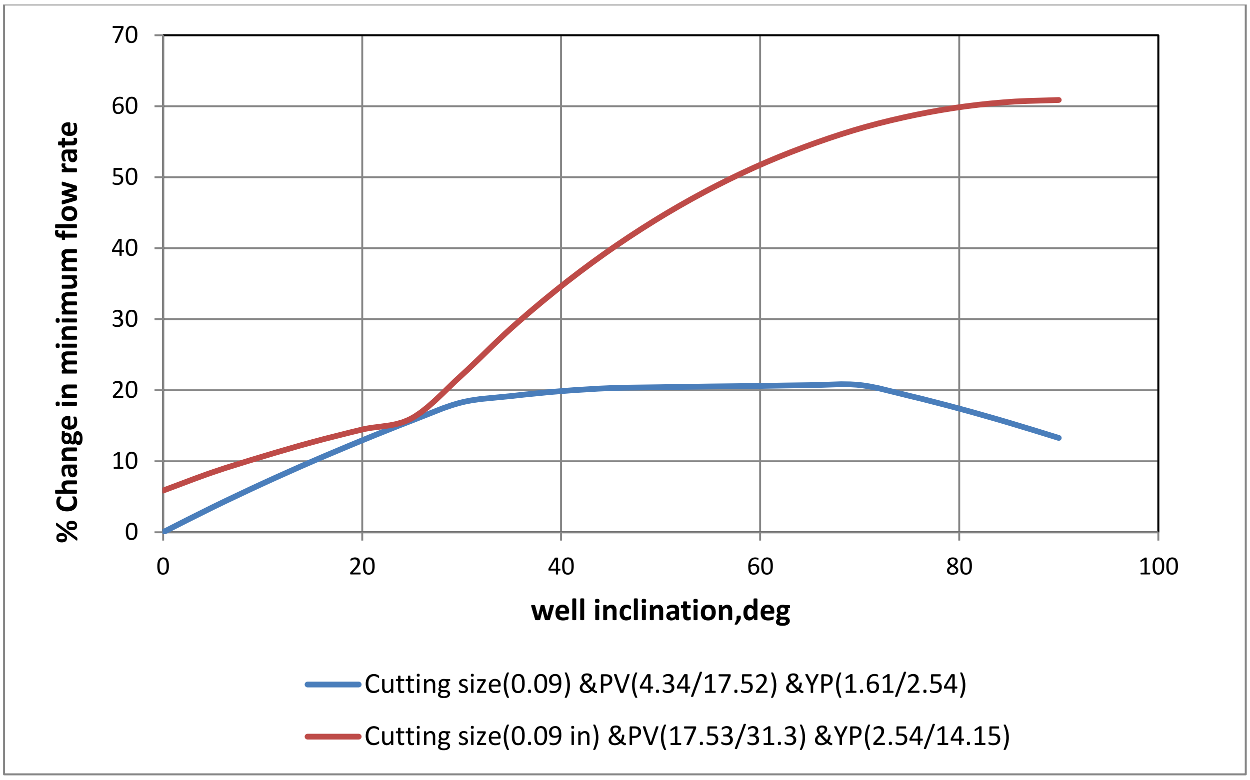


Figure 4.28: Relative increment between mud (1&2) & mud (2&3) with cutting size 0.09 in.

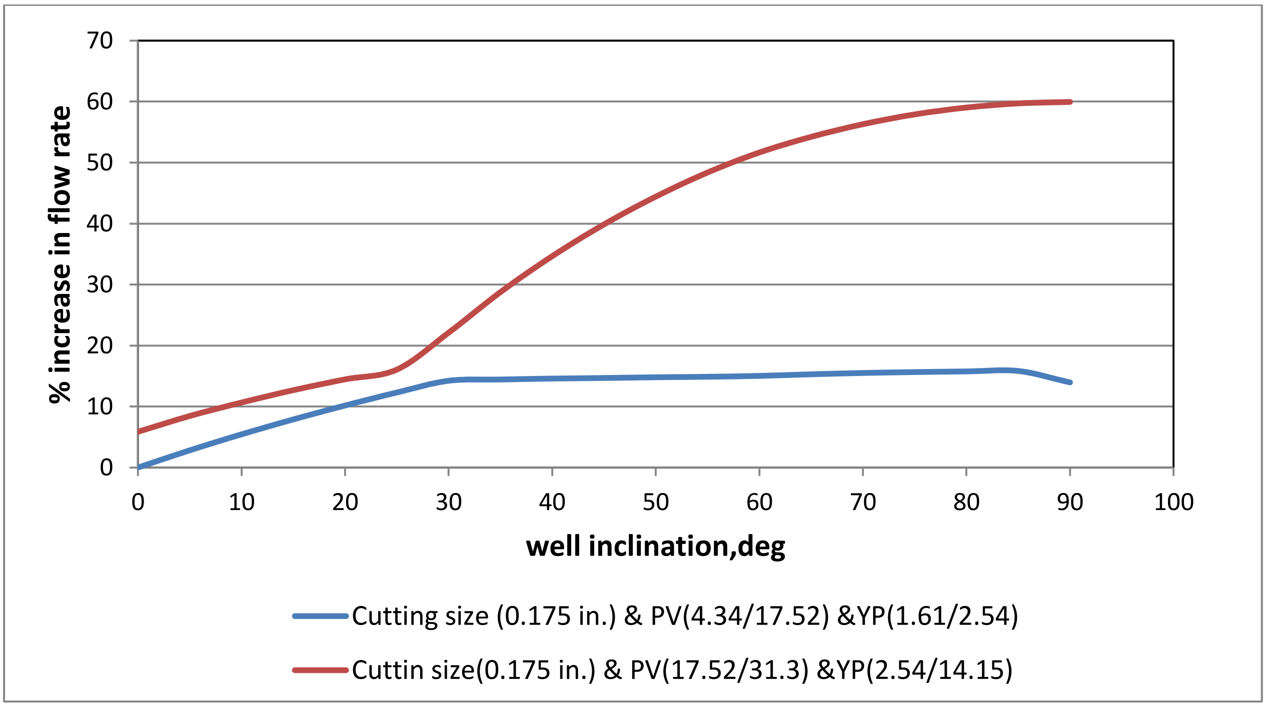


Figure 4.29: Relative increment between mud (1&2) & mud (2&3) with cutting size 0.175 in.

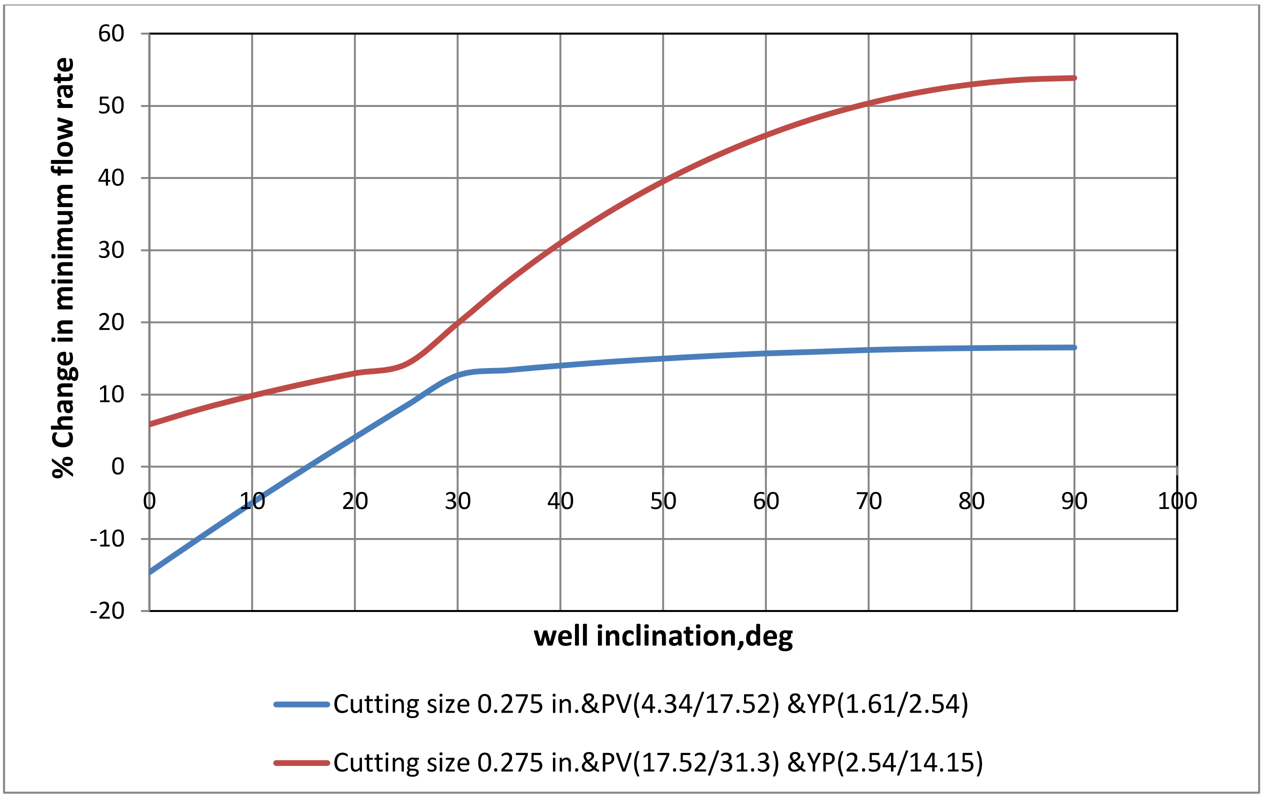


Figure 4.30: Relative increment between mud (1&2) & mud (2&3) with cutting size 0.275 in.

4.5.8.4 Comparisons of section 4.5.8.1 and 4.5.8.3

This part presents the comparisons of combined effect of viscosity/ RPM and combined effect of cutting size/viscosity. In both cases viscosity is common, but the difference is RPM and cutting sizes. The main objective here is to analyze the trends with respect to the fluid and operational parameter.

As can be seen from Figure 4.31 and Figure 4.32, the change of yield stress from 2.54 to 14.15 shows a significant effect than the lower yield stress change from 1.61 to 2.54. In general, the % increase is substantial irrespective of the cutting size and rotary speed. The Figure shows the relative change in flow rate requirement when the variation in yield stress is very small. For near vertical well inclination, the pipe rotations 50 RPM and cutting size (0.275in) show negative increment or decrease. The relatively higher plastic viscosity holds the particles in suspension.

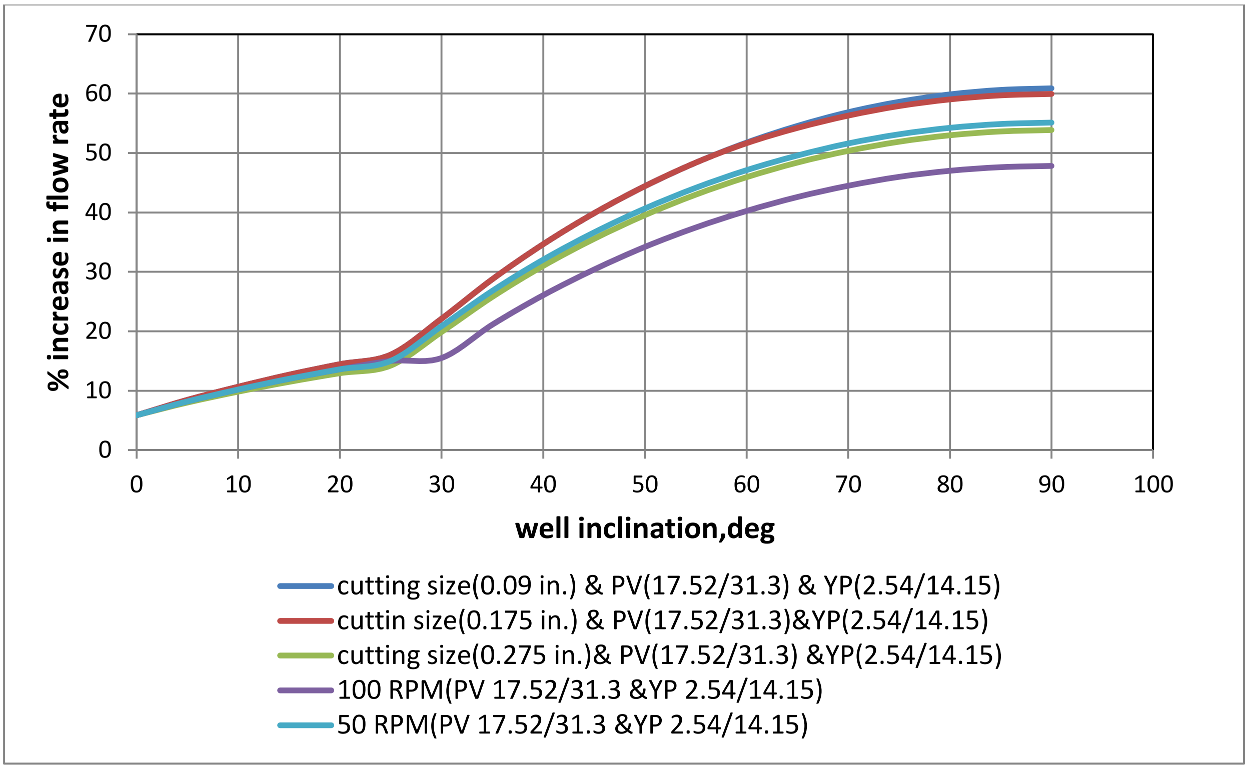


Figure 4.31:% Relative increment for different cutting sizes and pipe rotation combined with rheological parameters

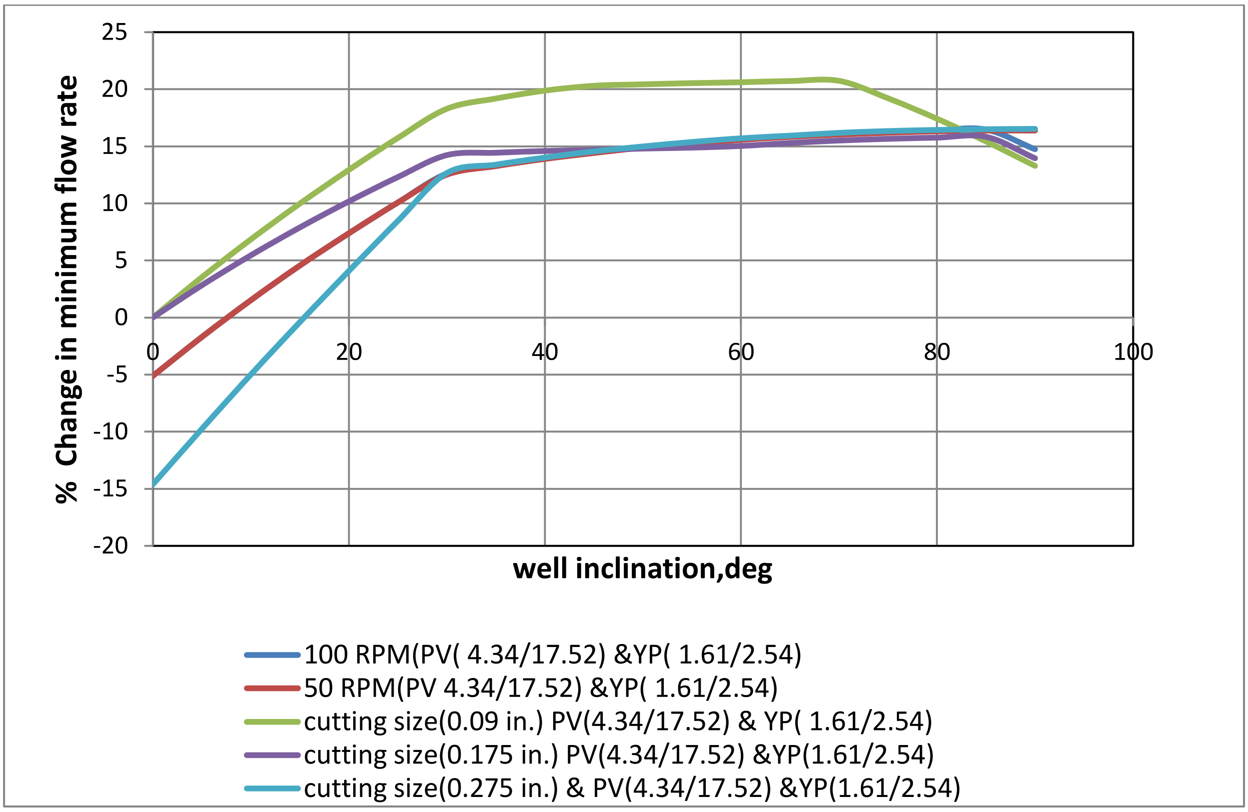


Figure 4.32: % Relative increment for different cutting sizes and pipe rotation combined with rheological parameters

5 Discussion of the simulation results

This section presents the discussion of the overall investigations. The simulation results in general agree in terms of trends of experimentally documented results. The thesis was focusing to analyze the sensitivity of parameters with respect to hole-cleaning phenomenon.

Hole-cleaning is a very complex process which involves fluid rheology, fluid mechanics and thermodynamics under the action of operational parameters.

In general the hole-cleaning becomes worse as well inclination increases from vertical to horizontal. Increasing flow rates can improve the cuttings-transport performance. As hole-inclination increases from vertical to horizontal, if appropriate flow rate is not used a cuttings-bed development will occur. Especially at inclinations between 40 and 60°, hole-cleaning is most difficult because of back sliding of the cuttings inside the wellbore.

The simulation study in this thesis investigated the effect of a single parameter keeping all other parameters constant, and a combined effect of two or more parameters. The following is a general discussion, which is based on the observed simulation results and the reviewed literature study.

Annular-Fluid Velocity

The simulation result shows that for any well inclination and under all operational conditions the higher the flow rate clean the well effectively. Laboratory and field scale experiments also reported this. However, the maximum allowable flow rate is determined by the maximum allowable equivalent circulation density (ECD) within the given drilling window. In addition, the capacity of the rig pumps to circulate the drilling fluid. Care should therefore be taken to optimize appropriate flow rate.

Hole-inclination Angle

Simulation and laboratory experiments have shown than as well inclination increases the hole cleaning efficiency becomes difficult. From Larsen’s experiment for instance one can observe that the effect of well cleaning changes gently between vertical and abut 30deg. As angle increase from 25 to 45/50 the cutting transport velocity shows a step transition and cutting sliding can occur in the case of connection where circulation stops or a sudden pump shutdown. This results a large amount of cutting accumulation and leads to drill string sticking problem.

Drill string Rotation

Simulation study confirms the results obtained from several laboratory studies on the impact of RPM on cutting transport. As pipe rotates, it agitates/initiates the settled lower part of cutting into fluid system, which exposes the cutting to high flow velocity. The RPM shows a moderate to significant on effect in improving the hole cleaning when combined with other operational and fluid and cutting properties From the 576 measured data, Bassal [37] have also shown a significant effect of drill string rotation on hole cleaning in directional well drilling. Larsen [5] on the other hand reported the work of [Iyoho, Okrajni, Becker], the effect of rotation in a concentric well geometry shows a minor effect. Larson also referred to the wellbore simulation study by Tormen, the effect of drill pipe rotation is minor in concentric well geometry. Ford et al's [12] experimental data observation also shows minor effect for large annulus and significant effect in smaller annulus.

The Wellplan ^{TM} simulator shows an impact reaching to 7.4% as compared to a non-rotating drill string provided at that given rate of penetration, cutting and drilling fluid properties. However, when changing these properties, the effect of RPM is also becomes different.

Rate of Penetration

The higher rate of penetration on leads to a higher cutting concentration in the annulus. The simulation result shows that a higher flow rate required ensuring a good cleaning. For drilling operation, a higher ROP has positive impact on drilling cost. The combined effect simulation study also shows that at a higher RPM with flow rate improves the hole cleaning. This as result prevents cutting accumulation problems, which indirectly causes drilling related problems such as excessive torque, drag, and mechanical drill sticking. These problems finally may lead to reducing rate of penetrations.

Drilling fluid Properties

In addition to balancing well pressure to control well instability problem, mud properties have also impact on cutting transport. Several experimental works have shown the hole-cleaning phenomenon in various mud systems. In this thesis work oil based and water based mud system were considered.

The properties of cutting (size, density) were investigated in low and high viscous water based mud systems. The study shows that the for a given cutting and operational parameters, viscosity and density of fluid have a significant effect on hole cleaning. Viscosity of the mud system is responsible for the suspension of particles in mud systems. During simulation, it is observed that the simulator is also sensitive to Q200 and Q100 values. However, I was not able to find any literature study documenting the effect of these readings.

Cuttings properties

The cutting properties such as (size, density, shape and concentrations) have effect on hole-cleaning. The simulation result shows that the smaller sized cutting behavior in less and higher viscous mud system behaves almost similar. As the cutting size increases, higher flow rate required to cleaning out of the hole.

The shape and the size of cutting generated is a function of the bit types used. Therefore these cutting parameters cannot be controlled except the concentration in terms of ROP. However, if more cuttings are produced, one must use a higher flow rate in order to prevent bed development in a well.

The simulation result shows that a smaller cutting size is easier to clean in less viscous fluid than the higher viscous fluid. The cutting transport can be improved under pipe rotations, which set the cutting in suspension and this makes easier for transport.

Pipe Eccentricity

Since the simulation arrangement is not suitable to construct a well and pipe at different eccentricity, the thesis don’t not have a look the degree of the impact caused by eccentricity. However, the effect is documented in several laboratory studies. (Example [5], [9] [15])

6 Summary and conclusion

Good hole-cleaning operation is one of the major factors for the successful drilling operation. On the other hand, poor hole-cleaning causes several drilling related problems such as high torque and drag, drill string sticking and poor hydraulics. As a result, this leads to higher operational costs for the industry.

Hole-cleaning is a very complex subject, which integrates fluid mechanics, fluid rheology, thermodynamics and mechanics. Since the introduction of hole-cleaning research several works have been carried out to investigate the behavior of cutting transport through modeling and experimental studies.

In this thesis, research works on hole-cleaning such as empirical, experimental and mechanistic are reviewed.

It is also reported that Well Plan^{TM} simulator [3] is industry standard and tested against field data. In this thesis work, the Well Plan^{TM} simulator is therefore used to evaluate the sensitivity of parameters associated with hole-cleaning. A simulation experimental setup was built based on real well geometry; operational, drilling fluid and cutting parameter. Based on the considered systems, several sensitivity parametric simulation studies were carried out.

The results show that the impact of parameters depends on various combinations parameters. The simulation results are in line with the reviewed research results.

- Increasing viscosity, density of fluid requires an increase flow rate
- Increasing ROP requires an increase flow rate
- Increasing well size requires an increase flow rate
- Increasing cutting density requires an increase flow rate
- Increasing cutting size requires an increase flow rate
- Increasing RPM reduces the flow rate required
- Increasing mud weight reduces the flow rate required

The thesis work is summarized as the following:

- ✓ The simulation result shows that operational parameters, drilling fluid and cutting parameters have effect on cutting hole cleaning. The results also confirm the trends and the behaviors of the laboratory documented cutting transport phenomenon. In general, poor hole cleaning occurs as the well inclination increases from vertical to horizontal. However, sufficient flow rate can improve hole-cleaning provided that the flow rate doesn't cause well fracturing problem. Therefore, during design phase hole-cleaning optimization study is crucial.

- ✓ Except well size effect, the simulation result shows that cutting transport phenomenon is more sensitive to other parameters in deviated well than in vertical well. The results are summarized in Table 6.1.

- ✓ As shown in section § 4.4.3.2, the choice of rheology model has effect on the cutting transport simulation result. It is therefore important to investigate which rheology model is best with respect to model prediction comparing with measured data.

- ✓ As shown in section § 4.5.6.2, the cutting transport simulation results in 1003ft and 11003ft wellbore length are the same. This shows that well length doesn't matter on flow rate required to clean the cutting out of the hole. An attempt was made to search if laboratory documented results exist. But, finally I was ended up without success.

- ✓ Based on the literature study, the reviewed papers reported that their models predict quite well their experimental data. However, the dynamics situation in drilling environment is very different from laboratory experimental environments. In literature, it is also reported that there is no a global model which describes all the cutting transport phenomenon very well [4]. It is therefore required more studies which describe dynamic processes of hole-cleaning along with using real time measured data. Recently, IRIS is trying to study in this line [26].

Table 6.1 summarizes some of the major investigation obtained from the simulation results discussed in Chapter 4. Please note that the result is based on the considered mud systems, cutting properties and operational parameters. When changing the simulation input parameters, we can get different values depending on their magnitude and combinations. Note that ‘’-‘’ means that % reduction and positive means that % increase

Mud system, operational & Cutting parameters used in the simulation	**Parameter**	**Parameter values between**	**% min flow rate change**		
			Vertical well	30deg inclined well	90deg inclined well
RPM= 50 ROP= 50ft/hr cutting density= 2.145 sg mud density= 12.5 ppg PV=17.52, YP=2.54 lbf/100sqft	Cutting size	change from 0.009-0.175 inch	0	0	0.59
		change from 0.09-0.275 inch	0	1.86	4.56
RPM= 50 PV= 17,52 cP YP=2.54 lbf/100sqft cutting diameter= 0.250 in cutting density= 2.145 sg mud density 12.5 ppg	ROP	change from 30 to 50ft/hr	0	6.96	5.8
		change from 30 -80 ft/hr	0	16.12	13.58
ROP=50ft/hr PV= 17.52cP YP=2544 lbf/100sqft cutting diameter= 0.250in cutting density= 2.145 sg mud density 12.5 ppg	RPM	change from 0 rpm- 50 rpm	0	-5.1	-5.2
		change from 0 rpm -100 rpm	0	-7.3	-7.45
RPM= 50 ROP= 50ft/hr Viscosity PV=17,52cP, YP=2.54 lbf/100sqft Cutting size=0.25 in Cutting density= 2.145 sg	Mud density	change from 8.5 ppg-10.5 ppg	4	-17	-17.4
		change from 8.5 ppg -12.5 ppg	6	-31.4	-32
PV=17,52cP, YP=2.541 lbf/100sqft Cutting size= 0.275 inch RPM= 50 ,ROP= 50ft/hr mud density= 12.5 ppg	Hole size	change from 8.5 inch-10.5	67.06	58.71	58.71
		change from 8.5 inch - 12.5 inch	136.63	126.38	126.38

Table 6.1: Summary of major simulation investigation

7 Future work

The simulation results show that cutting transport model prediction is sensitive to the effect of Q200 and Q100 values. In addition, the choice of rheology model also has effect on the cutting transport simulation result. Therefore, this thesis work proposes the following activities:

- ✓ One can in the future design several laboratory tests to investigate more the effect the above mentioned on the hole cleaning behavior

- ✓ Investigate which rheology model describe best cutting transport phenomenon

- ✓ Review more small scale and large scale cutting transport experimental data.
    - ○ Based on the reviewed experimental setup and inputs perform flow dynamics simulation. Finally compare the simulation results with the reviewed data
    - ○ Compare the small and the large scale measured data in order to investigate the impact of well length on cutting transport phenomenon.

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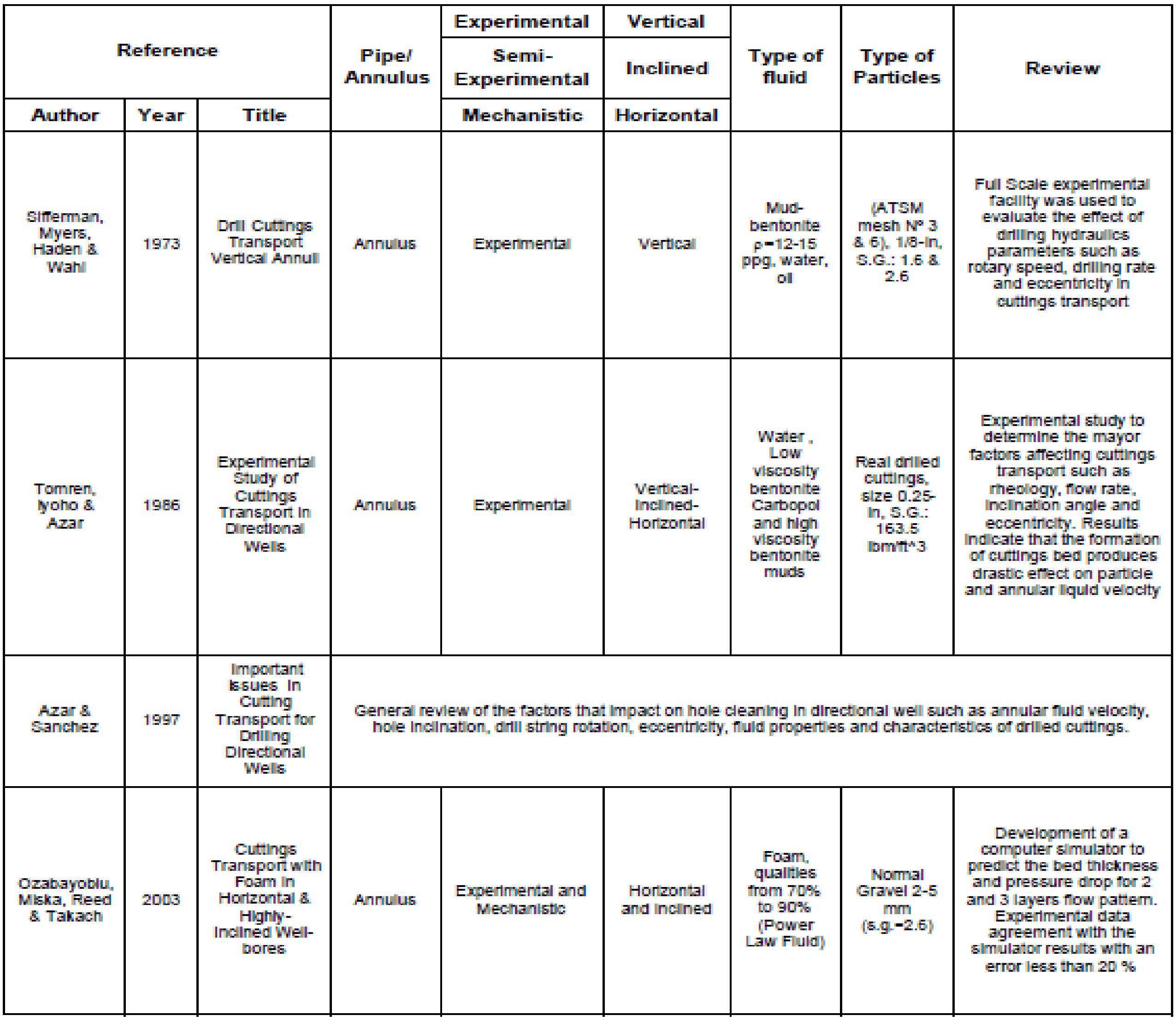
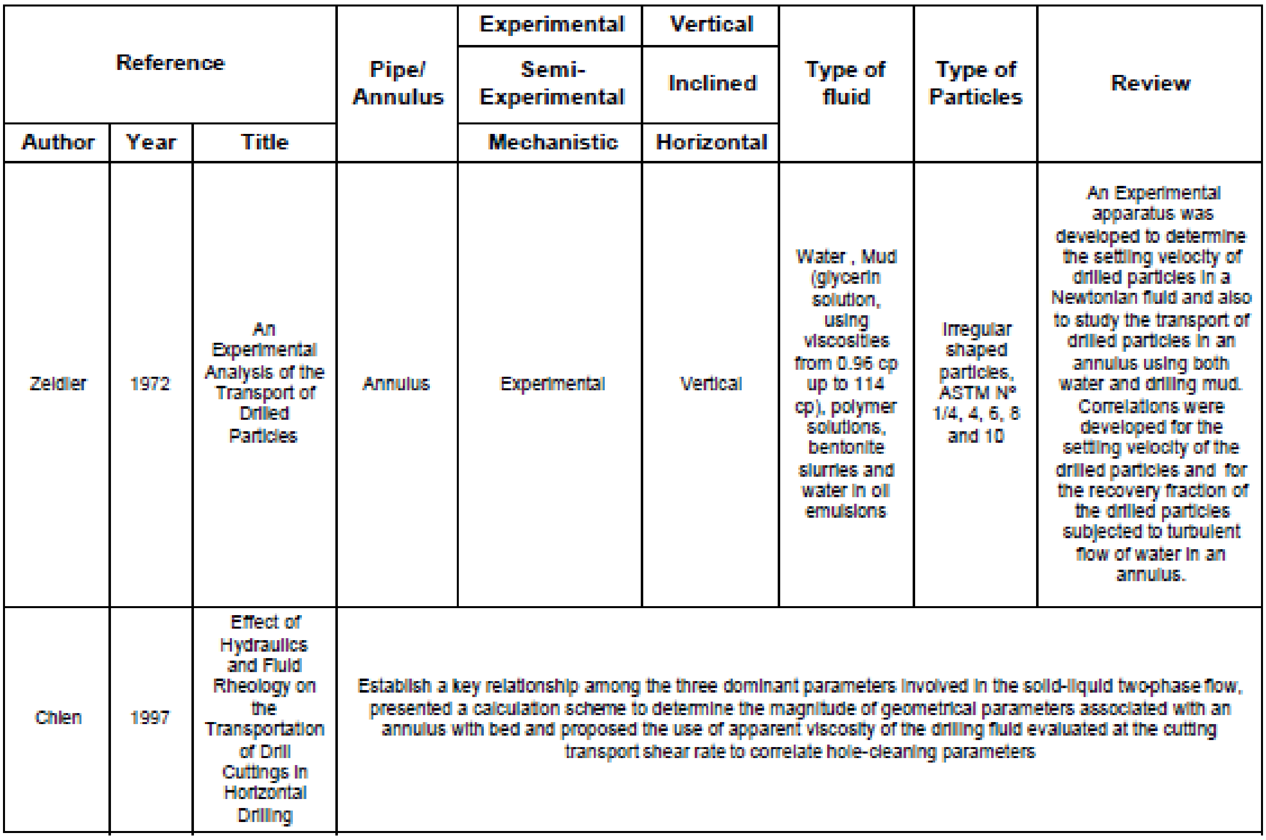
Appendix A: Reviewed Literature study

Tables A1 presents a summary of determinations of cutting lag in horizontal and deviated well. This is summarized by Augusto José Garcia-Hernande. The report was prepared for TUDRP Advisory Board Meeting,Tulsa-Oklahoma.The author performed a wide and details of literature studies. [38]



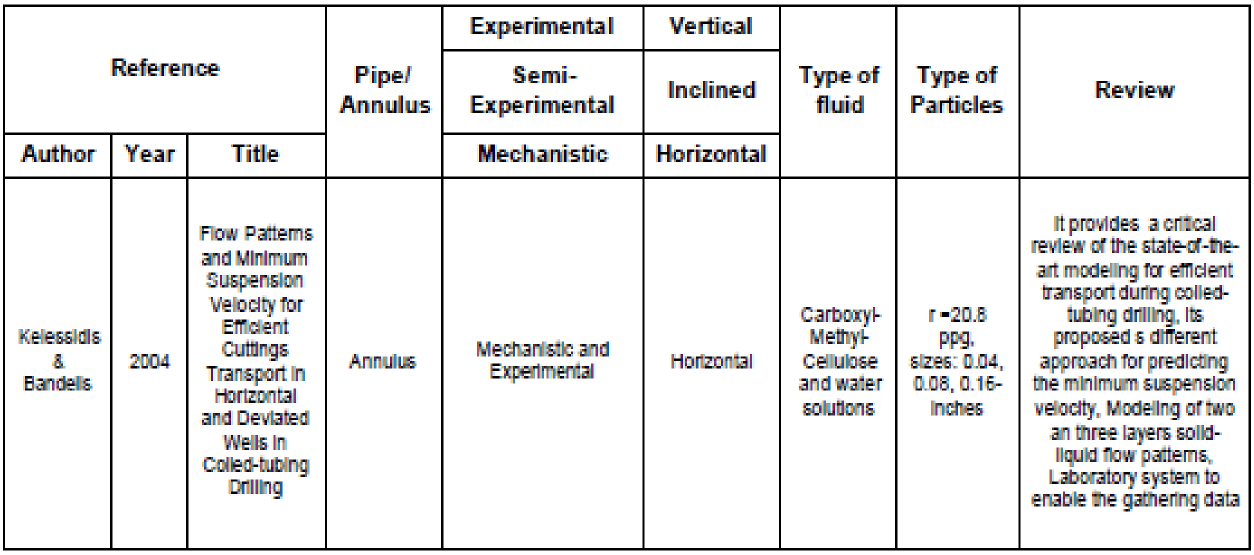
Reference			Pipe/ Annulus	Experimental	Vertical	Type of fluid	Type of Particles	Review
				Semi-Experimental	Inclined			
Author	**Year**	**Title**		**Mechanistic**	**Horizontal**			
Sifferman, Myers, Haden & Wahl	1973	Drill Cuttings Transport Vertical Annuli	Annulus	Experimental	Vertical	Mud-bentonite ρ=12-15 ppg, water, oil	(ATSM mesh N° 3 & 6), 1/8-in, S.G.: 1.6 & 2.6	Full Scale experimental facility was used to evaluate the effect of drilling hydraulics parameters such as rotary speed, drilling rate and eccentricity in cuttings transport
Tomren, Iyoho & Azar	1986	Experimental Study of Cuttings Transport in Directional Wells	Annulus	Experimental	Vertical-Inclined-Horizontal	Water , Low viscosity bentonite Carbopol and high viscosity bentonite muds	Real drilled cuttings, size 0.25-in, S.G.: 163.5 lbm/ft^3	Experimental study to determine the mayor factors affecting cuttings transport such as rheology, flow rate, inclination angle and eccentricity. Results indicate that the formation of cuttings bed produces drastic effect on particle and annular liquid velocity
Azar & Sanchez	1997	Important Issues in Cutting Transport for Drilling Directional Wells	General review of the factors that impact on hole cleaning in directional well such as annular fluid velocity, hole inclination, drill string rotation, eccentricity, fluid properties and characteristics of drilled cuttings.					
Ozabayoblu, Miska, Reed & Takach	2003	Cuttings Transport with Foam in Horizontal & Highly-Inclined Well-bores	Annulus	Experimental and Mechanistic	Horizontal and Inclined	Foam, qualities from 70% to 90% (Power Law Fluid)	Normal Gravel 2-5 mm (s.g.=2.6)	Development of a computer simulator to predict the bed thickness and pressure drop for 2 and 3 layers flow pattern. Experimental data agreement with the simulator results with an error less than 20 %

Table A-1.1: Literature review on cutting transport



Reference			Pipe/ Annulus	Experimental	Vertical	Type of fluid	Type of Particles	Review
				Semi-Experimental	Inclined			
Author	Year	Title		Mechanistic	Horizontal			
Zeidler	1972	An Experimental Analysis of the Transport of Drilled Particles	Annulus	Experimental	Vertical	Water , Mud (glycerin solution, using viscosities from 0.96 cp up to 114 cp), polymer solutions, bentonite slurries and water in oil emulsions	Irregular shaped particles, ASTM Nº 1/4, 4, 6, 8 and 10	An Experimental apparatus was developed to determine the settling velocity of drilled particles in a Newtonian fluid and also to study the transport of drilled particles in an annulus using both water and drilling mud. Correlations were developed for the settling velocity of the drilled particles and for the recovery fraction of the drilled particles subjected to turbulent flow of water in an annulus.
Chien	1997	Effect of Hydraulics and Fluid Rheology on the Transportation of Drill Cuttings in Horizontal Drilling	Establish a key relationship among the three dominant parameters involved in the solid-liquid two-phase flow, presented a calculation scheme to determine the magnitude of geometrical parameters associated with an annulus with bed and proposed the use of apparent viscosity of the drilling fluid evaluated at the cutting transport shear rate to correlate hole-cleaning parameters					

Table A-1.2: Literature review on cutting transport

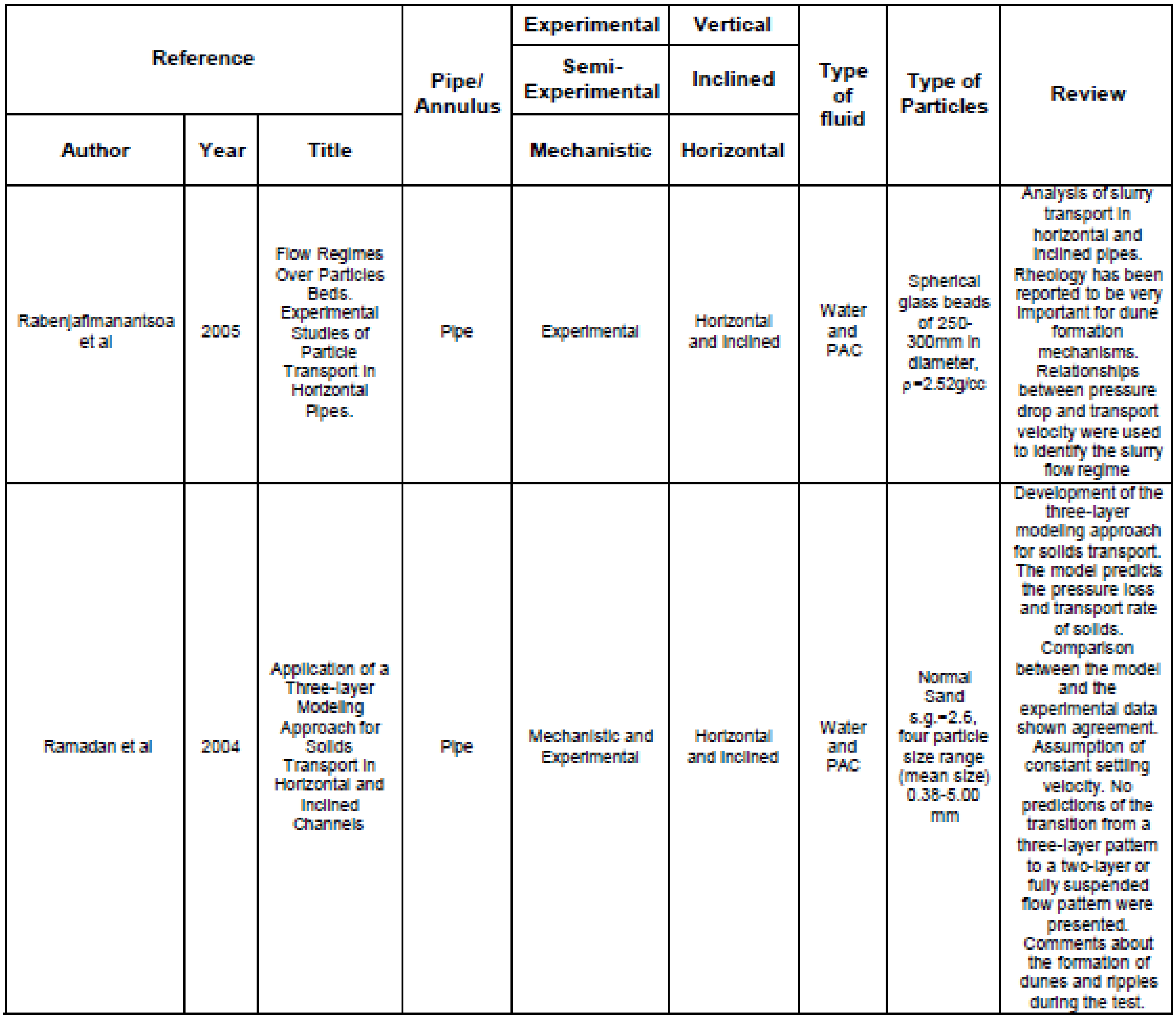


Reference			Pipe/ Annulus	Experimental	Vertical	Type of fluid	Type of Particles	Review
				Semi-Experimental	Inclined			
Author	Year	Title		Mechanistic	Horizontal			
Kelessidis & Bandelis	2004	Flow Patterns and Minimum Suspension Velocity for Efficient Cuttings Transport in Horizontal and Deviated Wells in Coiled-tubing Drilling	Annulus	Mechanistic and Experimental	Horizontal	Carboxyl-Methyl-Cellulose and water solutions	r =20.8 ppg, sizes: 0.04, 0.08, 0.16-inches	It provides a critical review of the state-of-the-art modelling for efficient transport during coiled-tubing drilling, its proposed s different approach for predicting the minimum suspension velocity, Modeling of two an three layers solid-liquid flow patterns, Laboratory system to enable the gathering data

Table A-2.1: Literature review on solid-liquid flow patterns

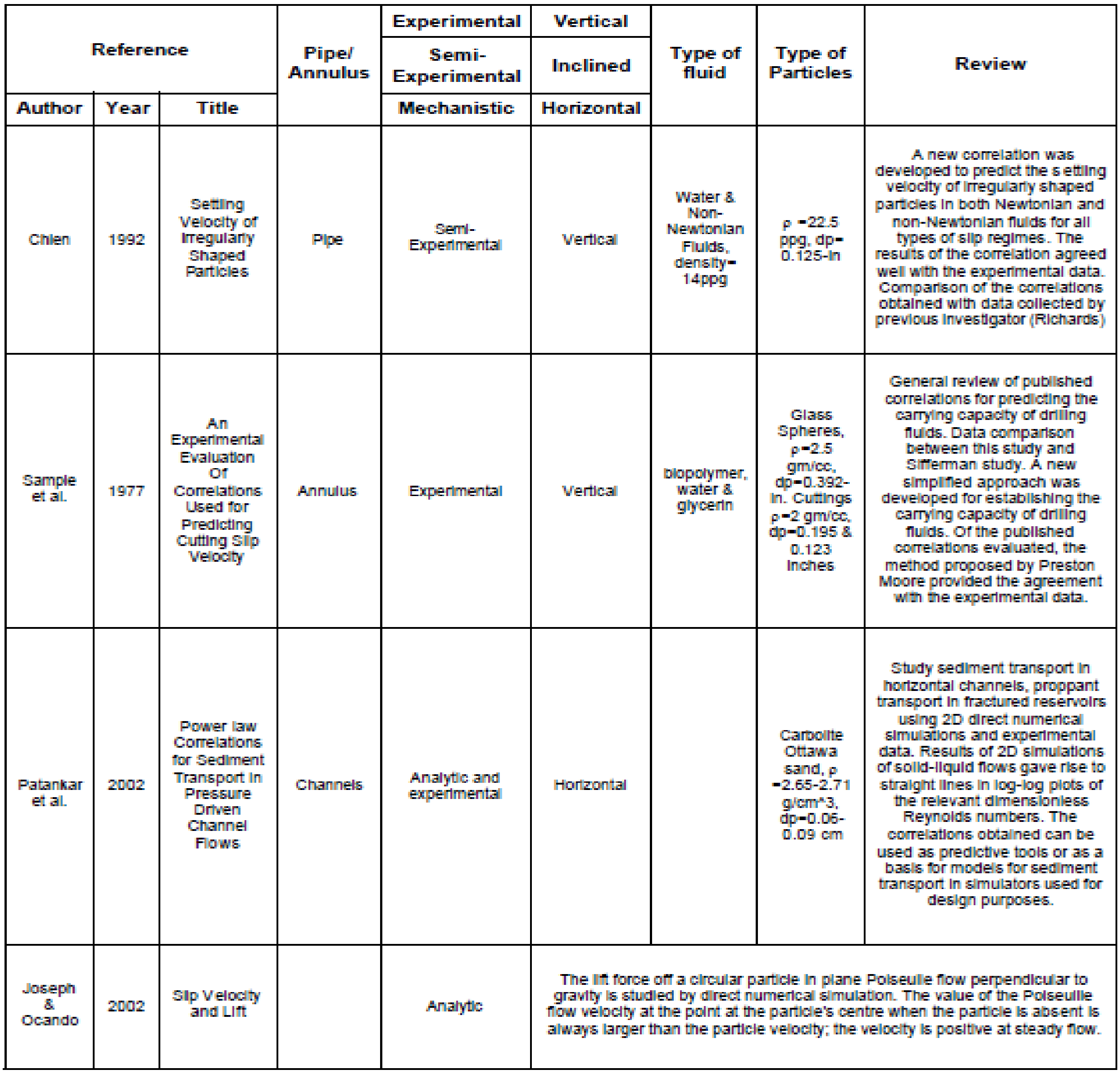
Reference			Pipe/ Annulus	Experimental	Vertical	Type of fluid	Type of Particles	Review
				Semi-Experimental	Inclined			
Author	**Year**	**Title**		**Mechanistic**	**Horizontal**			
Doron & Barnea	1995	Flow Pattern Maps for Solid-Liquid Flow in Pipes	Pipe	Mechanistic and Experimental	Horizontal	Water	Acetal Spheres, 3mm [1240 Kg/m3]	Flow Pattern maps were presented. The transitions between the flow patterns are then determined by means of a mechanistic three-layer model and compared with experimental data. The boundary between flow with a stationary bed and flow with a moving bed exhibits satisfactory agreement with the experimental data obtained.
Doron and Barnea	1994	Pressure Drop and Limit Deposit Velocity for Solid-liquid Flow in Pipes	Pipe	Mechanistic and Experimental	Horizontal	Water	Acetal Spheres, 3mm [1240 Kg/m3]	New experimental data on flow rates, pressure drop, delivered concentration and flow patterns for solid-liquid flow in pipes were presented. The three-layer model developed by Doron and Barnea in 1993 was compared to the new experimental data and other data from the literature, showing satisfactory agreement.
Hu	1995	Direct Simulation of Flows of Solid-liquid Mixtures	Simulation of a large number of solid particles motion in a flowing liquid using finite element technique based on moving unstructured grids. Using an developed numerical procedure, the Poiseuille flow of solid-liquid mixtures in a vertical channel was studied. For a sedimenting cylinder along the centerline of a channel, the computed terminal speed of the cylinder agrees with previously published numerical and theoretical results.					
Rabenjafimanantsoa et al	2005	Dunes Dynamics and Turbulence Structures Over Particles Beds, Experimental Studies and Numerical Simulations.	Pipe	Experimental and CFD Simulations	Horizontal	Water and PAC	Spherical glass beads of 250-300mm in diameter, ρ =2.52g/cc	Transport of particles in circular pipes involving formation of dunes in the transition flow regime. An Ultrasound Velocity Profile Monitoring Instrument was used to measure the instantaneous velocity profile over the dunes.

Table A-2.2: Literature review on solid-liquid flow patterns



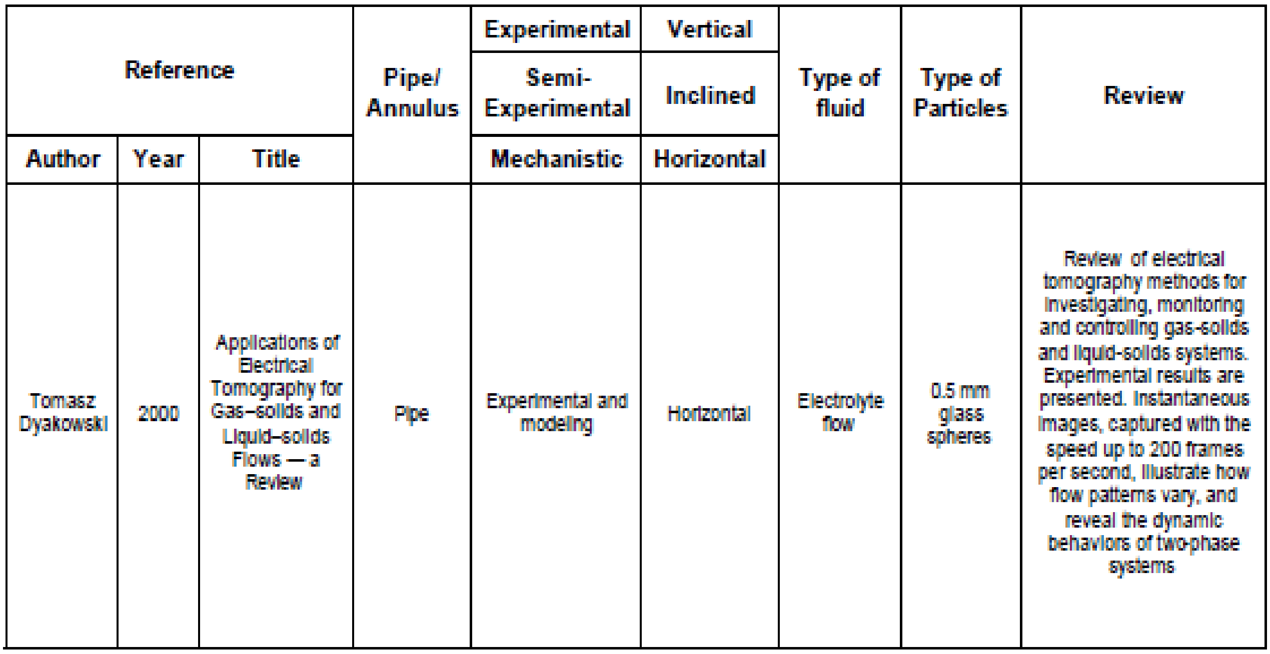
Reference			Pipe/ Annulus	Experimental Semi-Experimental Mechanistic	Vertical Inclined Horizontal	Type of fluid	Type of Particles	Review
Author	**Year**	**Title**						
Rabenjafimanantsoa et al	2005	Flow Regimes Over Particles Beds. Experimental Studies of Particle Transport in Horizontal Pipes.	Pipe	Experimental	Horizontal and Inclined	Water and PAC	Spherical glass beads of 250-300mm in diameter, ρ=2.52g/cc	Analysis of slurry transport in horizontal and inclined pipes. Rheology has been reported to be very important for dune formation mechanisms. Relationships between pressure drop and transport velocity were used to identify the slurry flow regime
Ramadan et al	2004	Application of a Three-layer Modeling Approach for Solids Transport in Horizontal and Inclined Channels	Pipe	Mechanistic and Experimental	Horizontal and Inclined	Water and PAC	Normal Sand s.g.=2.6, four particle size range (mean size) 0.38-5.00 mm	Development of the three-layer modeling approach for solids transport. The model predicts the pressure loss and transport rate of solids. Comparison between the model and the experimental data shown agreement. Assumption of constant settling velocity. No predictions of the transition from a three-layer pattern to a two-layer or fully suspended flow pattern were presented. Comments about the formation of dunes and ripples during the test.

Table A-2.3: Literature review on solid-liquid flow patterns



Reference			Pipe/ Annulus	Experimental Semi-Experimental Mechanistic	Vertical Inclined Horizontal	Type of fluid	Type of Particles	Review
Author	**Year**	**Title**						
Chien	1992	Settling Velocity of Irregularly Shaped Particles	Pipe	Semi-Experimental	Vertical	Water & Non-Newtonian Fluids, density=14ppg	ρ =22.5 ppg, dp=0.125-in	A new correlation was developed to predict the settling velocity of irregularly shaped particles in both Newtonian and non-Newtonian fluids for all types of slip regimes. The results of the correlation agreed well with the experimental data. Comparison of the correlations obtained with data collected by previous investigator (Richards)
Sample et al.	1977	An Experimental Evaluation Of Correlations Used for Predicting Cutting Slip Velocity	Annulus	Experimental	Vertical	biopolymer, water & glycerin	Glass Spheres, ρ =2.5 gm/cc, dp=0.392-in. Cuttings ρ =2 gm/cc, dp=0.195 & 0.123 inches	General review of published correlations for predicting the carrying capacity of drilling fluids. Data comparison between this study and Sifferman study. A new simplified approach was developed for establishing the carrying capacity of drilling fluids. Of the published correlations evaluated, the method proposed by Preston Moore provided the agreement with the experimental data.
Patankar et al.	2002	Power law Correlations for Sediment Transport in Pressure Driven Channel Flows	Channels	Analytic and experimental	Horizontal		Carbolite Ottawa sand, ρ =2.65-2.71 g/cm^3, dp=0.06-0.09 cm	Study sediment transport in horizontal channels, proppant transport in fractured reservoirs using 2D direct numerical simulations and experimental data. Results of 2D simulations of solid-liquid flows gave rise to straight lines in log-log plots of the relevant dimensionless Reynolds numbers. The correlations obtained can be used as predictive tools or as a basis for models for sediment transport in simulators used for design purposes.
Joseph & Ocando	2002	Slip Velocity and Lift		Analytic	The lift force off a circular particle in plane Poiseuille flow perpendicular to gravity is studied by direct numerical simulation. The value of the Poiseuille flow velocity at the point at the particle's centre when the particle is absent is always larger than the particle velocity; the velocity is positive at steady flow.			

Table A-3: Literature review on particle slip velocity



Reference			Pipe/ Annulus	Experimental Semi-Experimental Mechanistic	Vertical Inclined Horizontal	Type of fluid	Type of Particles	Review
Author	**Year**	**Title**						
Tomasz Dyakowski	2000	Applications of Electrical Tomography for Gas–solids and Liquid–solids Flows — a Review	Pipe	Experimental and modeling	Horizontal	Electrolyte flow	0.5 mm glass spheres	Review of electrical tomography methods for investigating, monitoring and controlling gas-solids and liquid-solids systems. Experimental results are presented. Instantaneous images, captured with the speed up to 200 frames per second, illustrate how flow patterns vary, and reveal the dynamic behaviors of two-phase systems

Table A-4: Literature review on particle tracking

Appendix B: Wellplan™ cutting transport models

The summary of the model are used in Well Plan ™[3].

Hole Cleaning Calculations

Calculate $n, K, \tau_y,$ and Reynold's Number

$$n = \frac{(3.32)(\log 10)(YP + 2PV)}{(YP + PV)}$$

$$K = \frac{(PV + YP)}{511}$$

$$\tau_y = (5.11K)^n$$

$$R_A = \frac{\rho V_a^{(2-n)}(D_H - D_P)^n}{(2/3)G_{fa}K}$$

Concentration Based on ROP in Flow Channel

$$C_o = \frac{(V_r D_B^2/1471)}{(V_r D_B^2/1471) + Q_m}$$

Fluid Velocity Based on Open Flow Channel

$$V_a = \frac{24.5Q_m}{D_H^2 - D_P^2}$$

Coefficient of Drag around Sphere

If $R_e < 225$ then,

$$C_D = \frac{22}{\sqrt{R_a}}$$

else,

$$C_D = 1.5$$

Mud carrying capacity

$$C_M = \frac{4g\left(\frac{D_c}{12}\right)(\rho_c - \rho)}{3\rho C_D}$$

Slip Velocity

If $V_A < 53.0$, then $V_{SV} = (0.00516)V_A + 3.0006$

If $V_A \geq 53.0$, then $V_{SV} = (0.02554)(V_A - 53.0) + 3.28$

Settling Velocity in the Plug in a Mud with a Yield Stress

$$U_p = \left[\frac{4}{3}\frac{gD_c^{1+bn}(\rho_c - \rho}{aK_b\rho_c^{1-b}}\right]^{\frac{1}{2-b(2-n)}}$$

Where:

$$a = 42.9 - 23.9n$$

$$b = 1 - 0.33n$$

Angle of Inclination Correction Factor

$$C_a = (\sin(1.33\alpha))^{1.33}\left(\frac{5}{D_H}\right)^{0.66}$$

Cuttings Size Correction Factor

$$C_s = 1.286 - 1.04D_c$$

Mud Weight Correction Factor

If $(\rho < 7.7)$,then

$$C_m = 1.0$$

else

$$C_m = 1.0 - 0.0333(\rho - 7.7)$$

Critical Wall Shear Stress

$$\tau wc = [ag\sin(\alpha)(\rho_c - \rho)D_c^{1+b}\rho^{b/2}]\frac{2n}{2n-2b+bn}$$

Where:

a = 1.732

b = -0.744

Critical Pressure Gradient

$$Pgc = \frac{2\tau wc}{r_h[1-(\frac{r_p}{r_h})^2]}$$

Total Cross Sectional Area of the Annulus without Cuttings Bed

$$A_A = \frac{\pi}{4}\frac{\left(D_H^2 - D_P^2\right)}{144}$$

Dimensionless Flow Rate

$$\Pi g_b = \Pi[8 \times \frac{\frac{n}{2(1+2n)}}{(a)\frac{1}{b}}]^{\frac{1}{2-(2-n)b}} \times (1-(\frac{r_p}{r_h})^2)(1-(\frac{r_p}{r_h})^{\frac{b}{2-(2-n)b}}]$$

Where:

a = 16

b = 1

Critical Flow Rate (CFR)

$$Q_{crit} = rh^2 \left[\frac{\rho g b^{\frac{1}{b}} r_h^{\left(\frac{1}{b+n}\right)}}{K\rho^{\left(\frac{1}{b-1}\right)}} \right]^{\frac{b}{2-b(2-n)}} \Pi_{gb}$$

Correction Factor for Cuttings Concentration

$$C_{BED} = 0.97 - (0.00231\,\mu_a)$$

Cuttings Concentration for a Stationary Bed by Volume

$$C_{bmc} = C_{BED}\left(1.0 - \frac{Q_m}{Q_{crit}}\right)(1.0 - \phi_B)(100)$$

Where:

D_B = Bit diameter

D_H = Annulus diameter

D_P = Pipe diameter

D_{TJ} = Tool joint diameter

D_C = Cuttings diameter

τ_y = Mud yield stress

G_{fn} = Power law geometry factor

R_A = Reynolds number

R_e = Particle Reynolds number

ρ = Fluid density

ρ_c = Cuttings density

V_a = Average fluid velocity for annulus

V_R = Rate of penetration, ROP

V_{CTV} = Cuttings travel velocity

V_{so} = Original slip velocity

V_{SV} = Slip velocity

V_{CTFV} = Critical transport fluid velocity

V_{TC} = Total cuttings velocity

K = Consistency factor

n = Flow behavior index

a, b, c = Coefficients

YP = Yield point

PV = Plastic viscosity

Q_C = Volumetric cuttings flow rate

Q_m = Volumetric mud flow rate

Q_{crit} = Critical flow rate for bed to develop

C_o = Cuttings feed concentration

C_D = Drag coefficient

C_m = Mud carrying capacity

C_A = Angle of inclination correction factor

C_S = Cuttings size correction factor

C_{mud} = Mud weight correction factor

C_{BED} = Correction factor for cuttings concentration

C_{bmc} = Cuttings concentration for a stationary bed by volume

U_{sp} = Settling velocity

U_s = Average settling velocity in axial direction

U_{mix} = Average mixture velocity in the area open to flow

α = Wellbore angle

ϕ_B = Bed porosity

μ_a = Apparent viscosity

λ_p = Plug diameter ratio

g = Gravitational coefficient

r_0 = Radius of which shear stress is zero

r_p = Radius of drill pipe

r_h = Radius of wellbore or casing

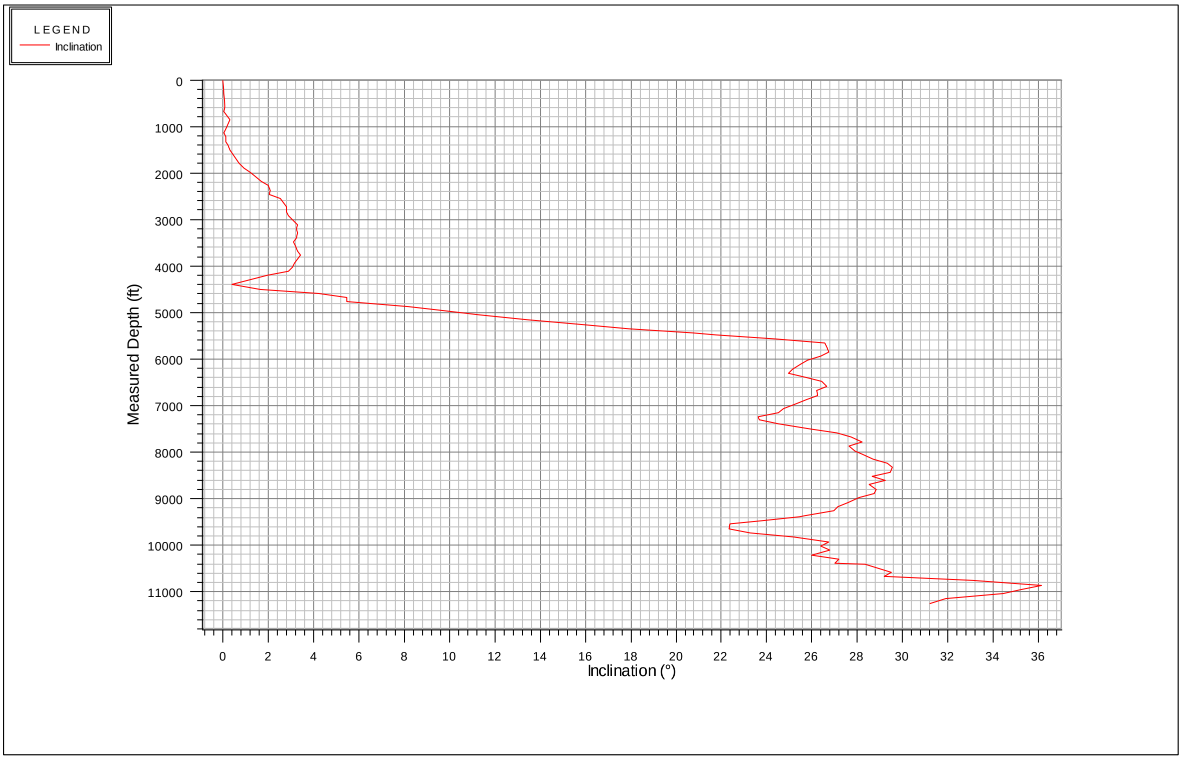
P_{cr} = Critical frictional pressure gradient

τ_{wc} = Critical wall shear stress

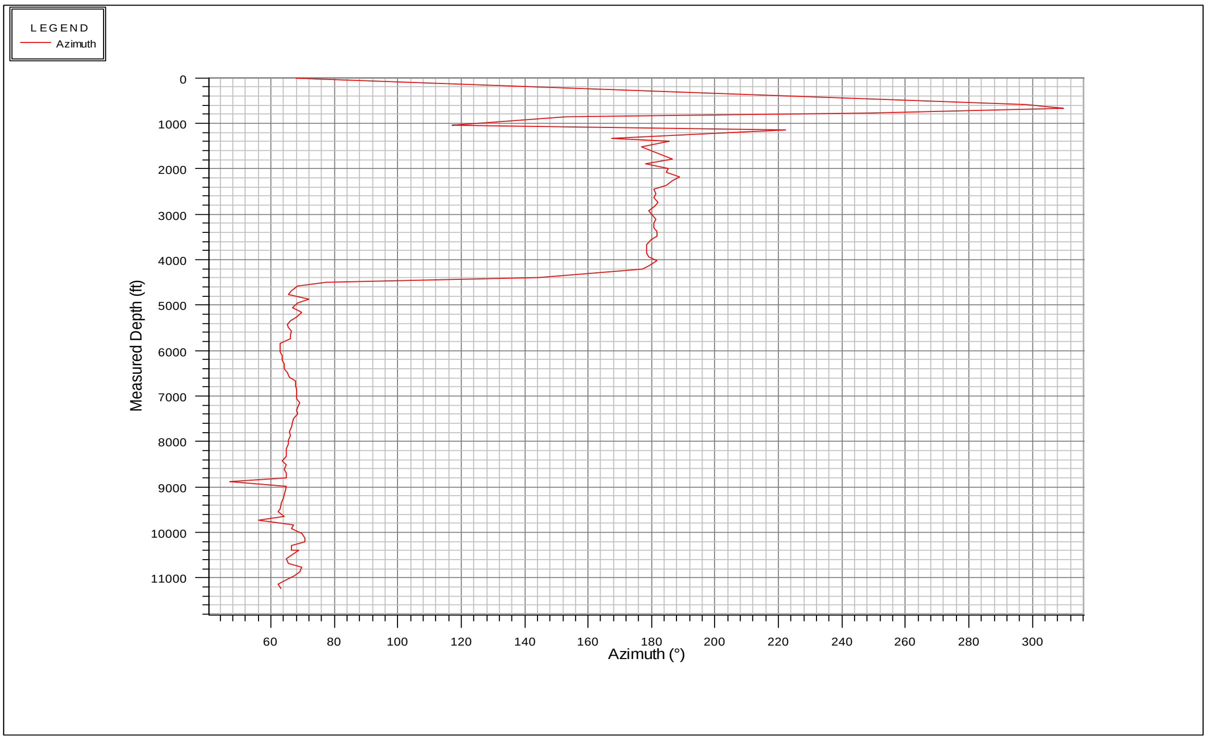
Appendix C: Well construction information

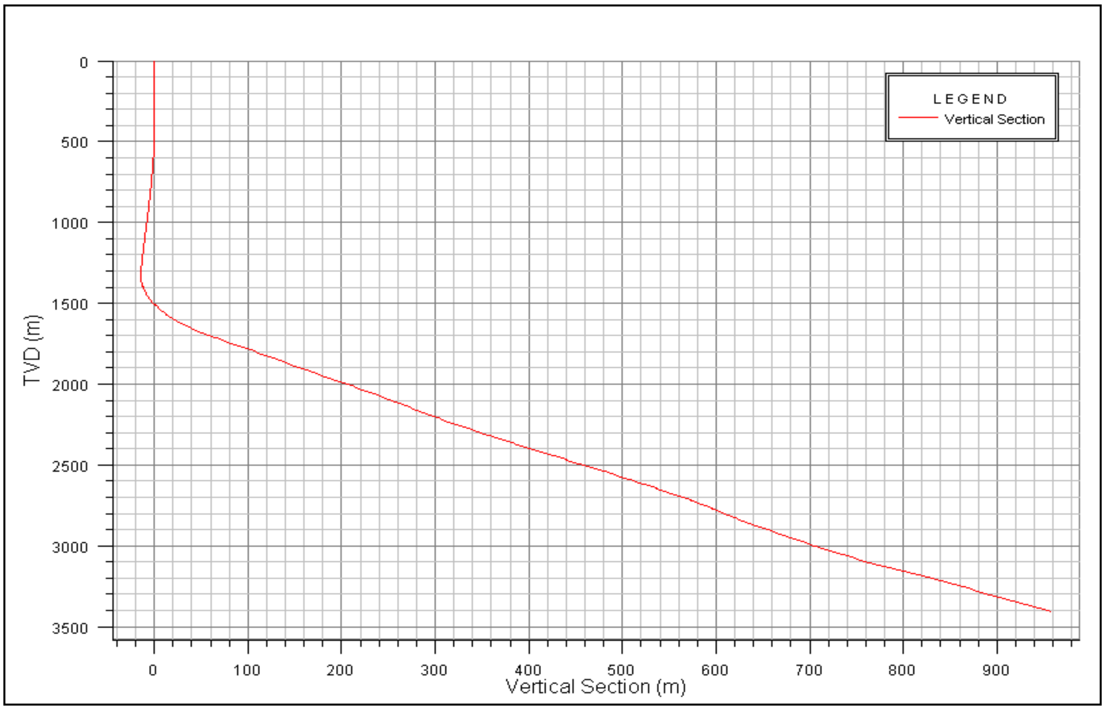
The input parameter for the simulation arrangement used are shown below.[Chapter 4]

Well inclination

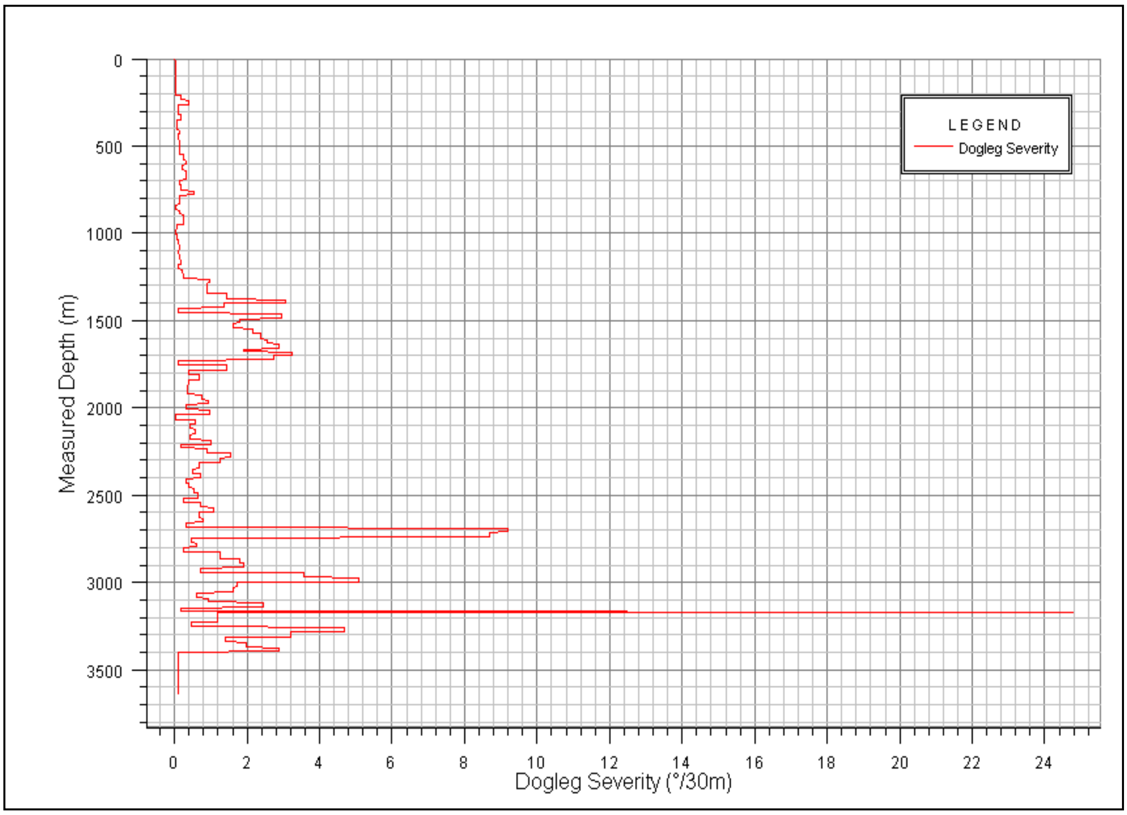


Azimuth





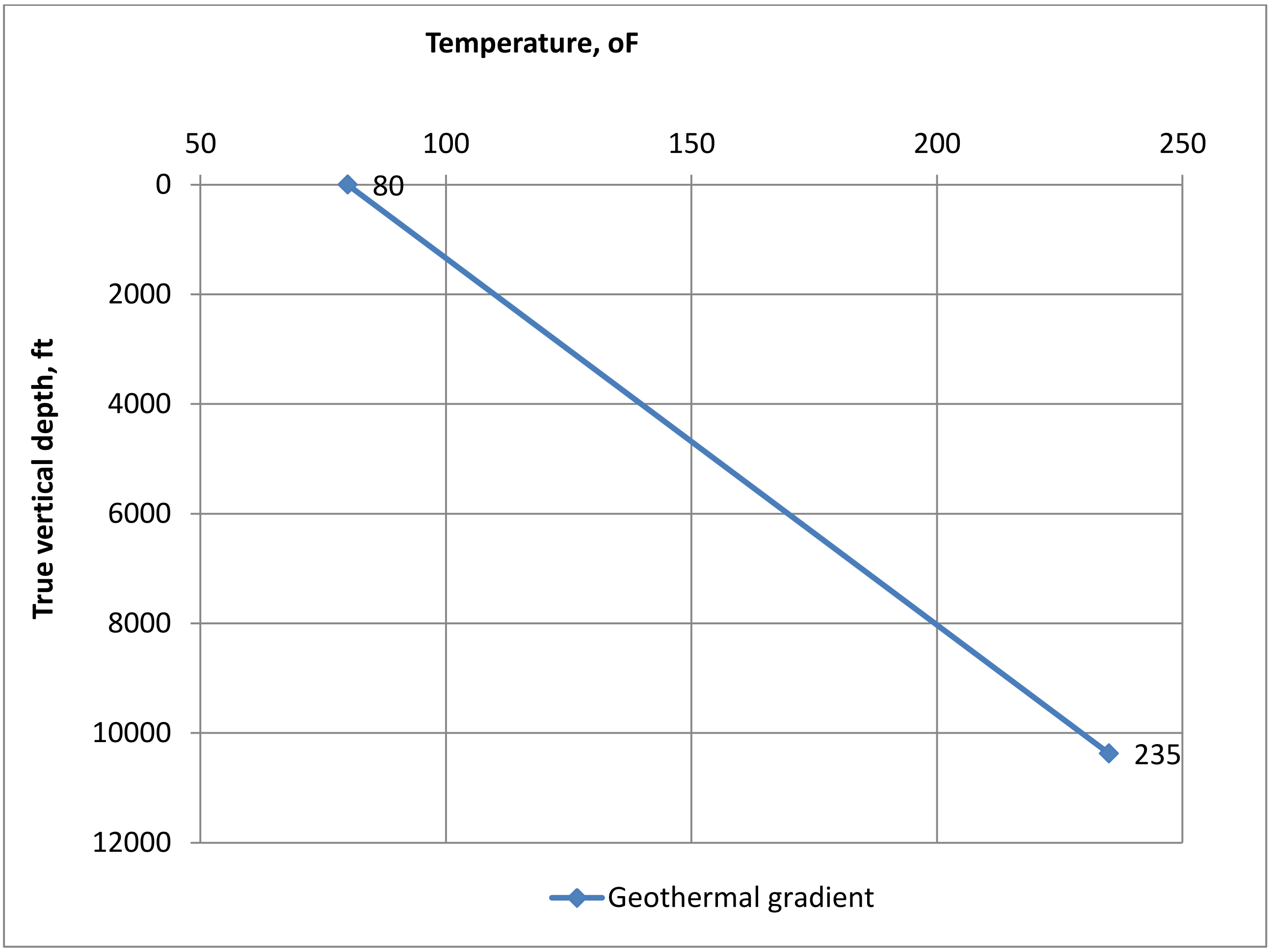
Graphical presentation of Vertical section



Graphical presentation of DLS

Geothermal gradient

The surface ambient temperature is 80 ^{o}F and the mud line is 40 ^{o}F. The geothermal gradient is 1.5 ^{o}F/100ft.



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Survey data

MD (ft)	INC (°)	AZ (°)
0	0	67,73
584,4	0,1	298
678	0,06	309,93
770,9	0,18	249,32
865,7	0,31	153,14
1045,2	0,15	117,22
1138,3	0,06	222,3
1232,9	0,13	197,58
1325,2	0,15	167,42
1398,1	0,23	185,68
1511,4	0,32	176,78
1797	0,72	186,62
1891,6	0,93	177,96
1987,3	1,22	185,23
2081,3	1,41	184,71
2175,4	1,71	188,92
2270,3	1,99	186,52
2366,7	2,11	184,49
2460,6	2,04	180,63
2555	2,56	181,46
2646,5	2,68	180,81
2732	2,8	181,89
2825,6	2,81	181,18
2918,2	2,89	178,95
3104,4	3,32	181,26
3195,7	3,26	180,69
3291	3,29	180,87
3386,9	3,24	181,77
3481,3	3,13	181,71
3575,5	3,22	179,61
3670,6	3,28	178,28
3764,1	3,42	178,59
3852,4	3,28	178,41
3947,8	3,18	179,06
4030,1	3,09	181,55
4117,1	2,9	179,33
4210,8	1,98	177,08
4395,7	0,41	144,38
4500	1,64	77,68
4585,1	4,25	68,48
4677	5,5	66,47

4774	5,47	65,41
4868,2	8,2	72,15
4957,1	9,73	68,56
5051,3	11,25	66,96
5154,8	13,44	69,7
5261,9	15,99	68,19
5341,2	17,94	66,03
5436,5	20,73	65,21
5490,5	21,77	65,44
5570,5	24,38	66,48
5648,7	26,55	66,19
5741,2	26,63	66,19
5847,2	26,74	62,77
5938,3	26,38	62,89
6026,5	25,79	63,01
6120,6	25,47	63,45
6212,6	25,15	63,59
6301	24,98	64,19
6397,1	25,72	64,27
6488,2	26,43	65,34
6582,3	26,64	65,78
6679,3	26,22	67,7
6774,2	26,23	67,67
6860,7	25,74	68
6953,4	25,33	68,18
7056,9	24,73	68,13
7150,9	24,53	68,98
7244,3	23,62	68,32
7307,6	23,69	68,09
7400,1	24,53	68,31
7490,9	25,89	67,26
7585,8	27,11	66,96
7681,8	27,72	66,36
7784,9	28,19	65,79
7866,2	27,61	66,06
7967,8	27,9	65,66
8052,2	28,21	65,41
8154,7	28,71	64,98
8248,1	29,33	64,88
8332,4	29,54	64,86
8425,5	29,43	63,48
8517,3	28,66	64,83
8610,1	29,23	64,27
8703,1	28,52	64,76

8797,4	28,81	64,82
8889,4	28,76	46,95
8985,7	28,09	64,81
9091	27,59	64,58
9170,2	27,13	64,17
9264	26,96	63,84
9365,7	25,68	63,24
9385,7	25,43	63,12
9476,6	23,77	63
9549,8	22,36	62,4
9644,5	22,33	64,24
9735,8	23,25	56,05
9832,1	25,18	67,26
9924,2	26,74	66,35
10020,9	26,39	69,8
10113,1	26,8	70,64
10202	25,97	70,79
10294,4	27,16	66,41
10391,6	27	66,47
10398,3	28,36	68,64
10577,5	29,49	64,84
10672,2	29,19	65,49
10766	33,1	69,66
10859,9	36,13	69,25
10954,1	35,22	67,54
11043,1	34,45	64,7
11140,6	31,91	62,37
11245,6	31,2	63,1

Appendix D: List of Figures

Appendix E: List of Tables

Appendix E: List of Nomenclature

C_D	Drag Coefficient
d_s	diameter of drill string [in]
D_H	diameter of hole [in]
D_P	diameter of pipe [in]
h	bedding height [in]
F_g,	Force of gravity [N]
F_b,	buoyancy force [N]
F_d,	Drag force [N]

F_L,	lift force [N]
F_{van}	Van der Waals dispersion, [N]
k	consistence index [lbf/100sqft]
n	flow behavior index [-]
R	radius of well/casing [in]
r	radius of the drill string [in]
Vs	Settling velocity[ft/min]
Vc	Cutting velocity [ft/min]
V_{ctf}	Critical transport fluid velocity [ft/min]
V_{fluid}	Fluid velocity [ft/min]
Q	flow rate [gpm]
μ_a	apparent viscosity [cP]
μ_p	plastic viscosity (PV) [cP]
τ_y	yield stress (YS)/ Yield point (YP) [lbf/100sqft]

Appendix F: List of abbreviation

ft/hr	foot per hour
pcf	pound per cubic foot
deg	degree
gpm	gallon per minute
ppg	pound per gallon
ECD	equivalent circulation density [sg]
ROP	rate of penetration [f/hr]
RPM	revolution per minute
WBM	Water based mud
OBM	Oil Based mud
PV	plastic viscosity, cP
YS or YP	yield stress / Yield point, [lbf/100sqft]