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Effects of Mud Rheology on Formation Pressure Control in Directional Wells.

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ABSTRACT

Directional wells often encounter complex hydraulic challenges due to increased annular friction, non-uniform cuttings transport, and variable pressure profiles. When mud rheology is not properly designed or controlled, these challenges can lead to inaccurate formation pressure estimation, wellbore instability, kicks, or lost circulation. Understanding the specific impact of mud rheology on formation pressure control in directional wells remains a critical engineering challenge requiring detailed investigation. Cuttings transportation during in non-vertical boreholes is necessary for oil and gas wells. Adequate cuttings removal from a well in drilling is critical for cost-effective drilling as high annular cuttings buildup often leads to high risk of stuck pipe, reduced rate of penetration and other impediments to standard drilling and completion procedures. This study investigates how rheological parameters influence the removal of cuttings in non-vertical boreholes. It contributes to work already done to ensure efficient hole cleaning process. In this study, the rheological parameters examined were the flow index (n), consistency index (K), plastic viscosity (PV), mud yield point (YP), YP/PV ratio, apparent viscosity and effective viscosity. Fifteen mud samples, three annular velocities (3.82, 2.86 and 1.91ft/sec) and three hole angles (30º, 45º and 70º) were considered. An Excel Spreadsheets program was used to determine the parameters. The results of this study show that, higher annular mud velocities are required for efficient hole cleaning in directional wells than in vertical wells. Increasing values of YP, YP/PV ratio and K promote effective cuttings transport while the value of n should be low. Effective and apparent viscosities also should be high.

Keywords: Mud Rheology, *Directional Wells, Formation Pressure,* Mitigation Strategies.

1.0 Introduction

Directional drilling has become a standard technique in modern oil and gas exploration due to its ability to reach reservoirs that are inaccessible via conventional vertical wells. As wells deviate from vertical, complex down-hole hydraulic conditions arise, influencing annular pressure distribution and overall wellbore stability. Mud rheology describing the flow behavior and deformation properties of drilling fluids plays a crucial role in carrying cuttings, maintaining hydrostatic balance, and managing formation pressures. Variations in rheological parameters such as plastic viscosity, yield point, and gel strength can significantly affect Equivalent Circulating Density (ECD), surge and swab pressures, and the risk of well control incidents. This study examines how mud rheology affects formation pressure control in directional wells and identifies strategies to optimize drilling fluid performance for safer and more efficient operations (Brock, 2017).

Increasing demand for petroleum and petroleum products worldwide has led to the exploration and production of oil from complicated reservoirs, and deep offshore is one of those. Formation of gas hydrates is also a severe problem associated with the production from deep water reservoirs at low temperature and high pressure. Suitable formulation of drilling fluid is one of the most important parameters for a successful drilling operation for such type of reservoirs. The main functions of the drilling fluids are to maintain wellbore stability, carry cuttings from the bottom of the hole to the surface, cool and lubricate drill bits, reduce formation damage, control subsurface pressure, allow adequate formation evaluation, seal permeable formations, prevent well control issues, convey hydraulic power and to gain data from the formation (Chu and Lin, 2019; Jensen et al., 2004). The properties of a drilling fluid include physical, chemical and rheological characteristics. While investigating these properties, it is very important to formulate the drilling fluid which will be environmentally friendly and low cost. In the drilling industry, water and clay formulates a simplest type of drilling fluid. Bentonite is a popularly used clay in the drilling industry because it can easily get hydrated by water and also act as a viscosifier. In addition, it has the capability to enhance hole cleaning ability when added to the drilling fluid (Wang, 2006).

As the development of deep water (offshore) drilling is rapidly increasing, the complexity associated with this type of drilling such as wellbore instability, lost circulation, hole cleaning capacity becomes a major issue (Zhao et al., 2019). The temperature of deep water reservoirs varies widely and hence, the drilling is highly challenging as the rheological properties of drilling fluids are significantly affected by temperature (Hu et al., 2011).

1.1 Drilling Fluid (Mud) Types

Drilling fluids can be broadly classified into three based on their constituents as shown in Fig. 1.1. Only diesel and mineral oil-based fluids are investigated in this research.

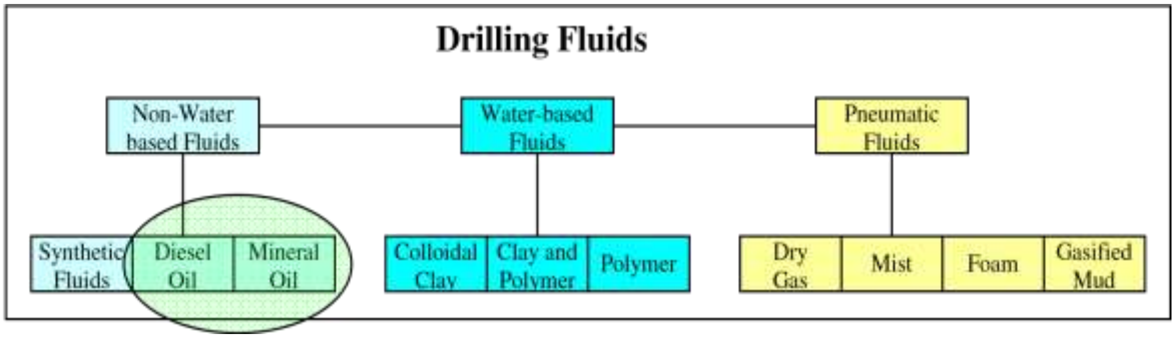

Figure 1.1: Drilling Fluids Classification by Composition

Fluids in general can be grouped into two according to their flow behavior: Newtonian and non-Newtonian. Fig. 1.2 illustrates the two groupings with examples.

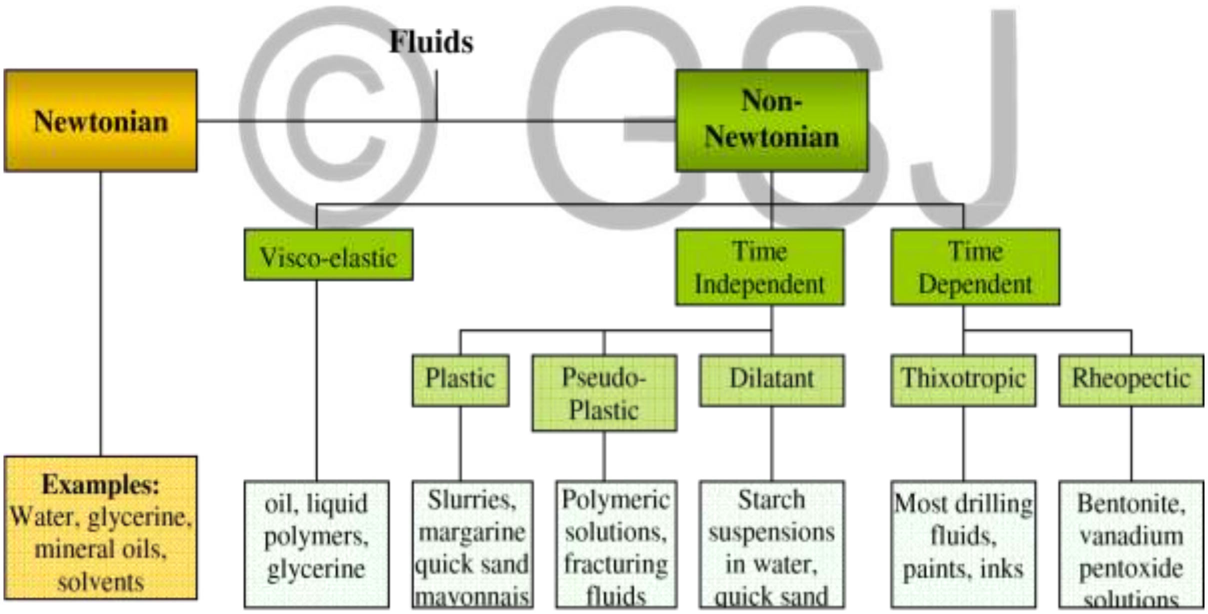

Figure 1.2: General fluid grouping by flow behavior

Newtonian fluids exhibit constant viscosity irrespective of the shear stress. For non-Newtonian, time independent fluid, shear stress is a function of shear rate. For time dependent fluids, stress – strain relationship depends on how the fluid has been sheared and on the previous history. Visco-elastic fluids are predominantly viscous but exhibit partial elastic recovery after deformation. Fluids exhibiting elastic properties are often referred to as memory fluids (Bachmann, 2012).

Most drilling fluids are non-Newtonian i.e. they have a viscosity value that is dependent on the rate of shear. Non-Newtonian, time independent fluids fall into 3 basic categories: Bingham plastics, pseudo plastics and dilatants fluids. A pseudo plastic fluid is one whose apparent viscosity or consistency decreases gradually with increase in rate of shear also known as shear thinning. For plastic fluids, shear force is not proportional to the shear rate and a finite shear stress is required to start and maintain flow. The direct opposite is a dilatant (shear thickening) fluid. Thixotropic fluids are characterized by increase in viscosity with time at constant shear rate. The reverse is true for rheopectic fluids (Alkan et al, 2014).

1.2 Statement of Problem

Many materials of engineering interest must be handled and transported as slurries or suspensions of insoluble particulate matter. Transportation of cuttings in no vertical boreholes is of no exception. Almost the same thing occurs whereby the cuttings act as the solids in the drilling fluid. In spite of the many technological advances that have accompanied the drilling of non-vertical boreholes, one significant remaining challenge is effective cuttings transport, particularly in deviated wells (Afrapoli, 2011).

The transportation of cuttings during drilling has a major influence on the economics of the drilling process. Problems that can occur as a result of inefficient hole cleaning from cuttings include reduced weight on bit, increase risk of pipe stuck and inability to attain the desired reach, reduced rate of penetration (ROP), extra cost because of the need of special additives in the drilling fluid, extra pipe wear, transient hole blockage which can lead to lost circulation and wasted time for wiper tripping. These problems have prompted significant research into cuttings transport during the past 50 years. (Kelessidis, 2004).

Hole cleaning relying on viscous fluids in laminar flow for drilling has proved to be inefficient because of the inability to rotate the string to agitate bedded cuttings. Alternatively, a high fluid flow to induce turbulent flow regime is more effective for hole cleaning, but difficult to achieve because of high friction pressures in the drill pipe. Therefore a bed of cuttings is almost always present in non-vertical boreholes. This study investigates how rheological parameters influence the removal of cuttings in non-vertical boreholes. It contributes to work already done to ensure efficient hole cleaning process.

1.3 Aim of the Study.

To analyze the influence of mud rheology on formation pressure control in directional wells and to evaluate how rheological properties can be optimized to enhance wellbore stability and drilling performance.

1.4 Specific Objectives of the Study.

i. To assess the relationship between mud rheology and formation pressure variations in directional wells.
ii. To analyze how rheological parameters influence ECD, surge/swab pressures, and cuttings transport.
iii. To identify operational risks associated with poor mud rheology in deviated well profiles.
iv. To propose effective mud design and circulation strategies for improved pressure control.
v. To evaluate mitigation measures to minimize well control challenges in directional drilling.

1.5 Significance of the Study

i. Enhances understanding of hydraulic behavior in deviated and horizontal well sections.

ii. Supports safer drilling operations by reducing risks of kicks, losses, and wellbore instability.

iii. Provides insights for drilling engineers to optimize mud programs for complex well trajectories.

iv. Contributes to the development of predictive models for real-time formation pressure management.

v. Helps reduce non-productive time (NPT) and overall drilling costs.

1.6 Limitations of the Study

i. Limited field data may reduce accuracy of some generalized conclusions.

ii. Results may vary with mud type (water-based vs oil-based) and drilling environment.

iii. Effects of extreme temperatures and pressures in ultra-deep wells are not fully covered.

iv. Some advanced well control technologies (e.g., automated ECD management) are outside this scope.

2.0 Literature Review

2.1 Fluid Rheology

Rheology is the study of the flow and deformation of fluids. Deformation is a change in shape in response to an applied force, which can be tension, compression, shear, bending, or torsion. A force applied to an area is called a stress. The fluids are mainly liquids but also soft solids flowing under conditions in which they flow without deforming elastically may be included. Rheology comes from the Greek word “rheos” which means to flow. The rheological characteristics of fluid are important in evaluating its ability to perform a specific function. It describes the relationships between the shear rate and the shear stress that causes movement. The study of rheology shows how materials, particularly liquids, respond to applied stress.

Rheological properties depend on the total solids content, temperature, pH-value, chemical conditioning and particle size.

One of the main issues of rheology is the definition and classification of materials. One way of characterizing a material is by its relaxation time, i.e. the time required to reduce the stress in the material by flow. Typical magnitudes of relaxation times for materials are:

Gases < 10^{-6} seconds

Liquids 10^{-6} – 10^{-2} seconds

Solids > 10^{-2} seconds

Another way of defining materials rheologically is by the terms viscous, elastic or viscoelastic. Gases and liquids are normally described as viscous fluids. An ideal viscous fluid is unable to store any deformation energy. Hence it is irreversibly deformed when subjected to stress. It flows and the deformation energy is dissipated as heat, resulting in a rise of temperature. Solids, on the other hand, are normally described as elastic materials. Ideal elastic material stores all imposed deformation energy and will consequently recover totally upon release of stress. A viscous fluid can therefore be described as a fluid which resists the act of deformation rather than the state of deformation, while an elastic material resists the act as well as the state of deformation. A number of materials show viscous as well as elastic properties, i.e. they store some of the deformation energy in their structure while some is lost by flow. These materials are called viscoelastic.

Viscosity is a measure of the resistance offered by a matter to a deforming force. Shear dominates most of the viscosity-related aspects of drilling operations. Because of that, shear viscosity (or simply, (''viscosity'') of drilling fluids is the property that is most commonly monitored and controlled. Retention of drilling fluid on cuttings is thought to be primarily a function of the viscosity of the mud and its wetting characteristics. Drilling fluids with elevated viscosity at high shear rates tend to exhibit greater retention of mud on cuttings and reduce the efficiency of high-shear devices like shale shakers. Conversely, elevated viscosity at low shear rates reduces the efficiency of low-shear devices like centrifuges, inasmuch as particle settling velocity and separation efficiency are inversely proportional to viscosity. (ASME, 2005).

2.2 Influence of Temperature and Pressure on the Rheology of Drilling Fluids

The rheological properties of drilling muds under downhole conditions may be very different from those measured at ambient pressures and temperatures at the surface.

At depth, the pressure exerted by the mud column may be as much as 20,000 pounds per square inch. The temperature depends on the geothermal gradient, and may be more than 500 °F, (260oC) at the bottom of the hole during a round trip. (Darley and Gray, 1988). Even quite moderate temperatures can have a significant, but largely unpredictable influence on the rheological properties. Muds may be thicker or thinner downhole than indicated at the surface, and an additive that reduces viscosity at the surface may actually increase the viscosity downhole.

Elevated temperatures and pressures can influence the rheological properties of drilling fluids in any of the following ways:

1. Physically: An increase in temperature decreases the viscosity of the liquid phase; an increase in pressure increases the density of the liquid phase, and therefore increases the viscosity. (Darley and Gray, 1988).

2. Chemically: All hydroxides react with clay minerals at temperatures above about 200 °F (94 °C). With low alkalinity muds, such as those treated with caustic tannate or lignosulfonate, the effect on their rheological properties is not significant, except to the extent that the loss of alkalinity lessens the effectiveness of the thinner. But with highly alkaline muds the effect may be severe,

depending on the temperature and the species of metal ion of the hydroxide. (Darley and Gray, 1988).

3. Electrochemically: An increase in temperature increases the ionic activity of any electrolyte, and the solubility of any partially soluble salts that may be present in the mud. The consequent changes in the ionic and base-exchange equilibria alter the balance between the inter-particle attractive and repulsive forces, and hence the degree of dispersion and the degree of flocculation. The magnitude and direction of these changes, and their effect on the rheology of mud, varies with the electrochemistry of the particular mud. (Darley and Gray, 1988).

2.3 Flow Patterns for Solid/Liquid Flow in Horizontal Concentric Annulus.

During the flow of solid/liquid mixtures in horizontal conduits, the liquid and solid phases may distribute in a number of geometrical configurations that depend on flow rates, conduit shape and size, fluid and solid properties, and inclination. Natural groupings - or flow patterns - exist within which the basic characteristics of the two-phase mixture remain the same. The main parameters determining the distribution of solids in the liquid (i.e., the flow patterns) are the liquid velocity, the solids loading, and the properties of liquid and solids (rheology and density of liquid, diameter and sphericity of solids). Observations of solid/liquid flow in horizontal pipes and annuli, even at low solids concentrations, suggest the flow patterns depicted in Fig. 2.1. (Kelessidis, 2004).

At high liquid velocities, the solids may be distributed uniformly in the liquid; normally, the correct assumption is made that there is no slip between the two phases (i.e., the velocity of the solids is equal to the velocity of the liquid). This flow pattern is normally observed for fairly fine solids (less than 1 mm in diameter) not normally occurring during drilling applications. This flow pattern is called the “fully suspended symmetric flow pattern” (Fig. 2.1a).

While the liquid-flow rate is reduced, there is a tendency for the solids to flow near the bottom of the pipe (or outer pipe of the annulus) but still be suspended, thus creating an asymmetric solids concentration, called the "suspended asymmetric flow pattern," with the solids still moving with the liquid (Fig. 2.1b).

A further reduction in the liquid-flow rate results in the deposition of solid particles on the bottom of the pipe. The solids start forming a bed, which moves in the direction of the flow. There may be some non-uniformly distributed solids in the liquid layer above. This pattern is called "the moving bed flow pattern." The velocity below this is commonly referred to as limit-deposit velocity, suspension velocity, or critical velocity (Fig. 2.1c).

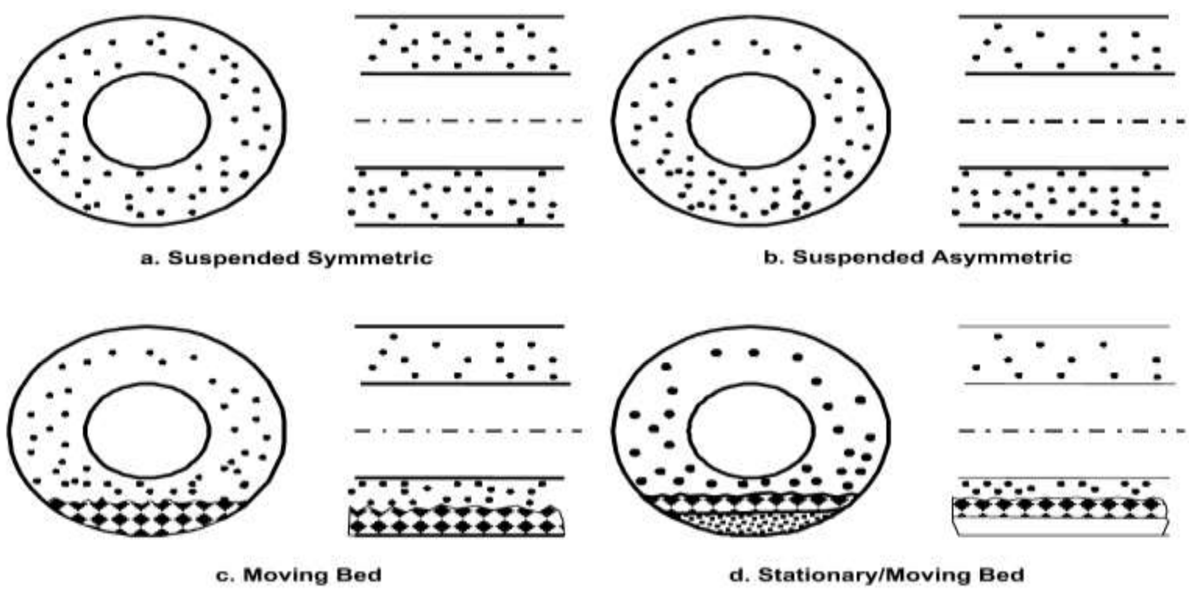

Figure 2.1: Flow patterns for solid/liquid flow in horizontal concentric annulus. (Kelessidis, 2004).

Reducing the liquid velocity further causes more and more solids to be deposited, resulting in three layers (Fig. 2.1d). A bed of solids that is not moving forms a stationary bed. A moving bed of solids forms on top of the stationary bed with a heterogeneous solid/liquid mixture above. There is a strong interaction between the heterogeneous solid/liquid mixture and the moving bed with some solids depositing on the bed and some re-entraining in the homogeneous solid/liquid mixture. An increase in the height of the solids bed decreases the available area for flow of the heterogeneous mixture. This results in higher mixture velocities leading to an increase in the erosion of the bed by the mixture, thus establishing equilibrium for this flow pattern.

At lower liquid velocities, the solids pile up in the pipe (or annulus), and full blockage may occur. Experimental evidence and theoretical analysis indicate that this may occur at a relatively high solids concentration not encountered during normal drilling operations. It may also occur if cuttings transport is inefficient and results in high solids concentration, especially in sections in which large cross-sectional areas exist, example in annulus washouts. (Kelessidis, 2004).

2.4 Theory of Cuttings Transport

The ability of a drilling fluid to transport cuttings to the surface is generally referred to as "carrying capacity". From an engineering point of view, cuttings transport is dependent on well bore inclination, cuttings slip velocity, flow regime, rotary speed of the drill pipe, fluid rheology, fluid flow rate, rate of penetration, cuttings size and shape, wellbore geometry and other drilling parameters.

One of the primary functions of the drilling fluid is to bring drilled cuttings to the surface in a state that enables the drilling-fluid processing equipment to remove them with ease. To achieve this end, quick and efficient removal of cuttings is essential. In aqueous-based fluids, when drilled solids become too small to be removed by the solids-control equipment, they are recirculated downhole and dispersed further by a combination of high-pressure shear from the mud pumps, passing through the bit, and the additional exposure to the drilling fluid. (ASME, 2005).

2.5 Hole Cleaning

Efficient hole cleaning is especially important in drilling non-vertical boreholes since problems can be exacerbated due to the smaller clearances between the drilling BHA and wellbore. For good hole cleaning, vertical flow is preferable because cuttings fall in the opposite direction to the drilling mud flow. For an inclined well, the direction of cuttings settling is still vertical, but the fluid velocity has a reduced vertical component. This decreases the mud's capability to suspend drilled cuttings. At a high angle of inclination a particle that sediments through the mud has a short distance to travel before striking the borehole wall. Once it reaches the wall, the particle has little chance to be entrained because local fluid velocities near the wall are very low and insufficient to re-entrain the particle into the flow. Consequently, the residence time of the particle in the annular space increases significantly resulting in a higher concentration of cuttings in the wellbore. This brings about formation of a cuttings bed that creates operational problems. (Sifferman and Becker, 1990).

Generally, turbulent flow provides more efficient cleaning and particle-carrying characteristics but occurs at higher fluid velocities than laminar flow. Geometries and fluid properties commonly encountered in drilling non-vertical boreholes mean that it is often difficult, and frequently impossible, to achieve turbulent flow. (Williams et al., 2001).

Maximum flow rate in non-vertical boreholes operations is typically constrained by the down hole motor specification and limitations on surface pressure.

In hole cleaning, the optimum flow regime will vary depending upon the hole angle at which the wellbore is situated. Hole cleaning in highly deviated wellbores is more challenging and critical than in vertical wells. In inclined wells, the fluid velocity has a reduced vertical component that may not be sufficient to transport all the cuttings particles to the surface. These conditions cause the formation of a "cuttings bed" on the low side of the wellbore. The most difficult angle to clean is from 30 – 60 degrees from vertical, where a laminar or turbulent regime works equally well (or poorly). The optimum regime for the vertical (< 30 degrees) and highly deviated (> 60 degrees) wellbores are laminar and turbulent, respectively. (Q'Max Solutions Inc., 2009).

Since cuttings which originate from a highly deviated or horizontal well must travel through all of the wellbore angles and finally to vertical before leaving the well, the safest rheological profile is one with a laminar flow regime. A turbulent pattern will also work as long as the annular velocity can be maintained.

Hole cleaning techniques may be divided into three classes:

i. High-viscosity gel-like fluids in laminar flow.

ii. Medium-viscosity fluids in laminar/turbulent flow.

iii. Low viscosity fluids in turbulent flow.

2.6 Key Factors in Hole Cleaning

1. Fluid velocity/pump rate: Fluid velocity is an important player in the hole cleaning equation. However for fluids in laminar flow, fluid velocity alone cannot efficiently remove cuttings from the deviated wellbore. Fluid velocity can disturb cuttings lying in the cuttings bed and push them up into the main flow stream. However, if the fluid has inadequate carrying capacity, then many of the cuttings will quickly fall into the cuttings bed once again and the cycle repeats. (Patrick et al., 1996).

2. Down hole Rheology**:** Drilling fluid theological properties are normally measured at 120 °F [49 °C] and at atmospheric pressure. However, in a drilling situation the circulating drilling fluid is exposed to a varied set of temperature and pressure conditions. Data collected over many years' shows that drilling fluid viscosities vary with temperature and pressure, something especially important for invert emulsions. For best results when studying fluid flow behaviours and evaluating problems in the field, it is important to apply the drilling fluid rheological parameters either measured or calculated under the actual down hole conditions. (Patrick et al., 1996).

3. Drill pipe Eccentricity: In a deviated well, the drill string will usually not lie in the center of the hole (as is often assumed), but will fall toward the lower side of the hole due to gravitational effects. Hence, the position of the drill string can be described as eccentric. The narrow gap of the eccentric annulus usually lies on the low side of the hole under the drill pipe and the wide gap

usually lies above the drill pipe. Drill pipe eccentricity is usually considered positive when the narrow gap lies below the drill pipe and negative when it lies above.

Researchers have investigated the effect of drill pipe eccentricity on velocity distribution in the eccentric annulus and have shown it to have major impacts.

In order to limit the development of cuttings beds, it is desirable to maintain certain levels of fluid velocity where the beds may accumulate. In deviated wellbores, cuttings beds largely accumulate under the eccentric drill pipe in the narrow gap. For that reason attention should be paid to optimizing fluid velocities under the eccentric drill pipe to better clean the deviated annulus of drilled cuttings. (Patrick et al., 1996).

4. Particle Settling Velocity**:** The rate at which drilled cuttings fall through a static drilling fluid has great importance for cuttings transport in vertical and deviated wellbores. Accurate prediction of particle settling rates is especially critical for highly-deviated wellbores because the vertical gaps below the drill pipe can be quite narrow when the drill pipe is in a highly eccentric position. (Patrick et al., 1996).

5. Pipe Rotation**:** Pipe rotation of the drill string can aid in cleaning the wellbore of drilled cuttings. The movement of the drill string through the cuttings bed forces the cuttings into the main flow stream, where they can be carried farther up the deviated annulus. The bending and whipping action of the drill pipe during rotation and back reaming causes frequent fluctuations in drill pipe eccentricity.

6. Vertical and Near Vertical Intervals**:** In near vertical wellbores the cuttings particles generally remain in suspension the whole time they are in the wellbore. When the pumps are on and the drill string is rotating the particles may be assumed to be distributed uniformly throughout the fluid, though variations in cuttings concentration with measured depth may occur with varying rates of penetration (ROP). In addition, cuttings may accumulate at higher concentrations in regions where

the hole diameter goes through an expansion and the annular velocity subsequently decreases, such as a washout or in a drilling riser.

2.6. Effects of Mud Rheology on Formation Pressure Control

i. Increased ECD in Deviated Wells: Higher viscosity and gel strength elevate frictional pressure losses, increasing ECD and risk of exceeding fracture gradients.

ii. Surge/Swab Pressure Sensitivity: Poor rheology can cause excessive surge while running pipe or swab when pulling out, potentially inducing kicks.

iii. Cuttings Bed Formation: Inadequate rheology leads to poor hole cleaning, especially in high-angle sections, causing annular pressure build-up.

iv. Wellbore Instability: Improper rheology may lead to insufficient support for weak formations, causing collapse or pack-off.

v. Inaccurate Pressure Prediction: Non-Newtonian behavior complicates hydraulic modeling, leading to miscalculations in formation pressure control.

vi. Increased Torque and Drag: Thick, poorly optimized mud increases drag, affecting tripping and circulation efficiency.

2.7 Mitigation Strategies

i. Rheology Optimization: Adjust PV, YP, and gel strength to ensure adequate carrying capacity while minimizing ECD.

ii. Use of Low-Viscosity Sweep Pills: Helps remove cuttings beds in high-angle sections without excessively increasing ECD.

iii. Hydraulic Modeling and Real-Time Monitoring: Employ software for ECD prediction and adjust mud properties accordingly.

iv. Managed Pressure Drilling (MPD): Provides precise control over annular pressures.

v. Use of Thinners and Rheology Modifiers: Chemical adjustments to regulate viscosity changes with temperature and pressure.

vi. Optimized Pump Schedules: Adjust flow rates to manage surge/swab pressures.

vii. Proper Hole Cleaning Practices: Regular circulation, back reaming, and wiper trips.

2.8 Discussion of Results

A wide range of cuttings concentration was observed in this study. The rheological parameters examined were the power law flow index, consistency index, plastic viscosity (PV), mud yield point (YP), YP/PV ratio, apparent viscosity, effective viscosity and the Fann viscometer dial readings. Power law fluid was used in this study. Three annular mud velocities were considered, (3.82, 2.86 and 1.91 ft/sec). Hole inclinations of 30o, 45o and 70o from the vertical were taken into account.

Findings show that mud rheology significantly affects formation pressure stability, with YP and PV being strong determinants of ECD behavior. Higher gel strengths improve suspension but can lead to elevated surge pressures during tripping. Enhanced rheology improves cuttings transport, reducing annular blockage but must be balanced to avoid exceeding fracture gradients. Simulation results confirm that optimized rheology reduces pressure fluctuations, stabilizes the wellbore, and improves overall drilling efficiency.

2.8.1 Effects of some of the rheological parameters on critical annular velocity

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

In Fig. 2.2, it can be shown that, an increase in the flow index (n) increases the critical annular velocity. The amount of cuttings concentration in the annulus will therefore be on the decrease as the value of n increases because of the tendency of n to cause an increase in the fluid velocity in the annulus.

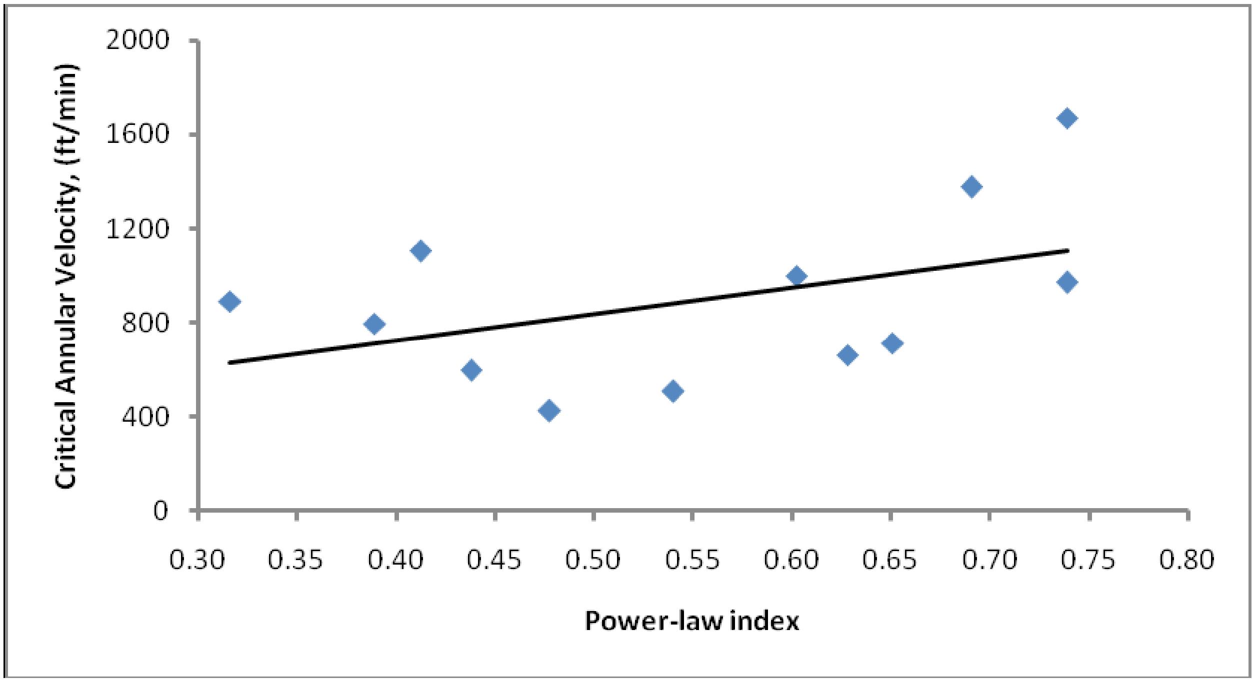

Figure 2.2: Effect of power-law index on critical annular velocity.

Fig. 2.3 shows how the power-law consistency index influences the critical annular velocity which aids in efficient hole cleaning process. According to this study, the effect of consistency index corrected for the annulus on the critical annular velocity is minimal. Thus, the figure shows that increasing values of K increase critical annular velocity but only slightly. It can be said that the critical annular velocity is directly proportional to the consistency index.

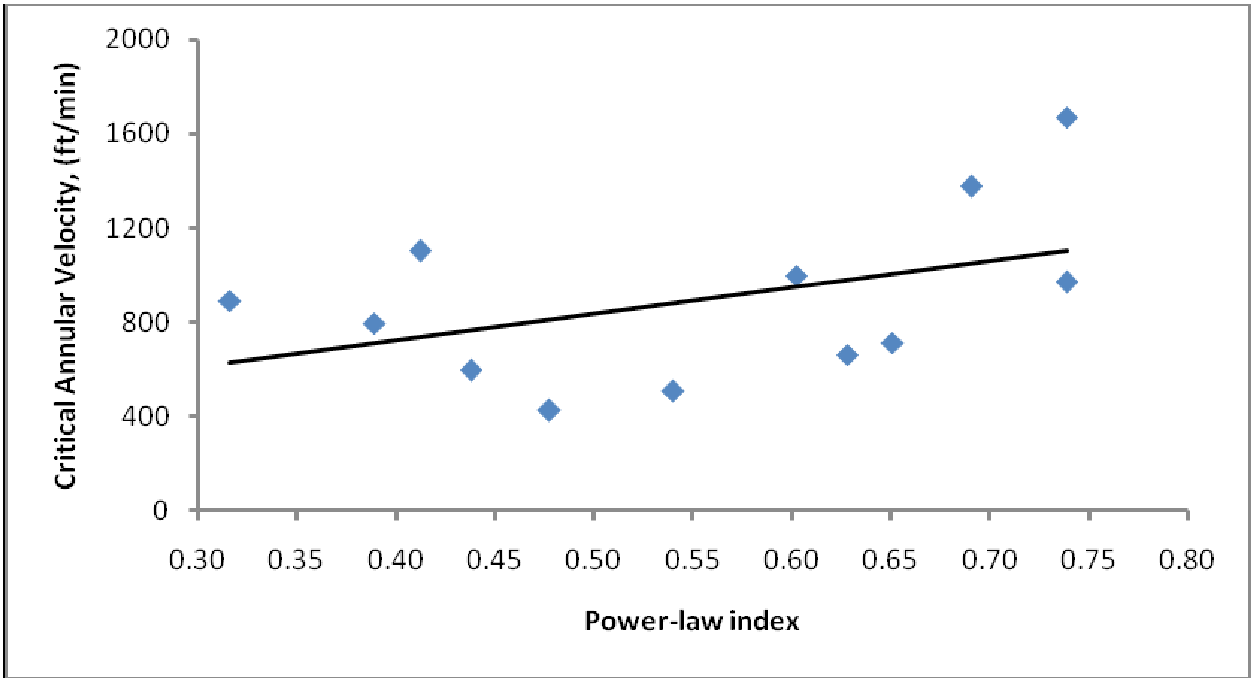

Figure 2.3: Effect of power-law consistency index on critical annular velocity Critical annular velocity is seen to increase significantly with an increase in plastic viscosity.

This is depicted in Fig. 2.4. To ensure effective and successful cuttings removal from the annulus it is then advisable to increase the plastic viscosity which will indirectly increase the critical annular velocity required to accomplish the hole cleaning purpose.

A graph of critical annular velocity versus yield point can also be seen in Fig. 2.4. The trend of this plot is similar to that in Fig. 2.4. It shows a significant increase in critical annular velocity as the yield point is increased. Therefore a high yield point will ensure a good hole cleaning process. The combined effect of yield point and plastic viscosity on the critical annular velocity was also investigated under this study.

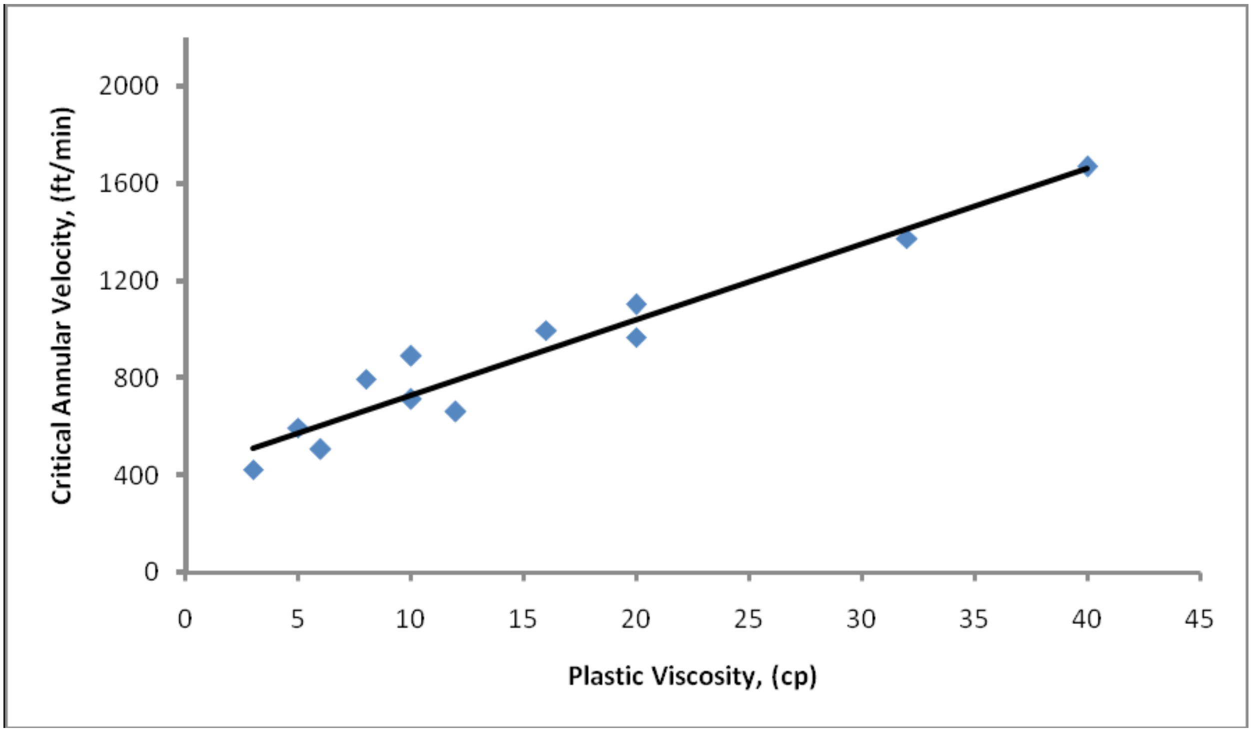

Figure 2.4: Effect of yield point on critical annular velocity.

2.9 Effects of Rheological Parameters on Cuttings Concentration

In order to know the influence that rheological parameters have on the amount cuttings generated in the annulus, various plots were made.

Figures 2.5 (a) and (b) are plots of cuttings concentration versus apparent viscosity.

Both plots show that, cuttings concentration declines with increasing value of apparent viscosity. Again, it was observed that, Fig. 2.5 (b) which has a lower annular mud velocity recorded higher values of cuttings concentration when compared to Fig.

2.5 (a). For efficient hole cleaning process, it is then important to resort to high apparent viscosity values while maintaining a high annular mud velocity.

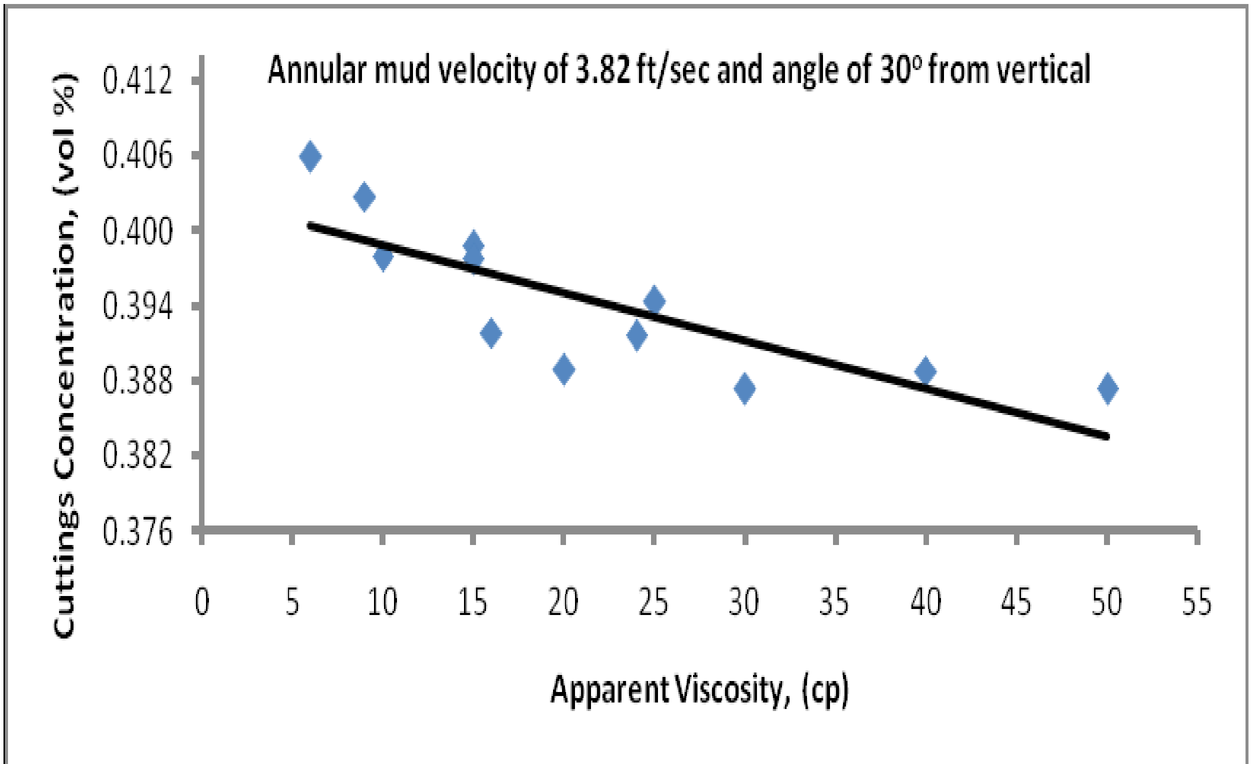

Figure 2.5 (a): Annular cuttings concentration vs. Apparent viscosity fo annular velocity of 3.82 ft/sec and angle of 30° from vertical.

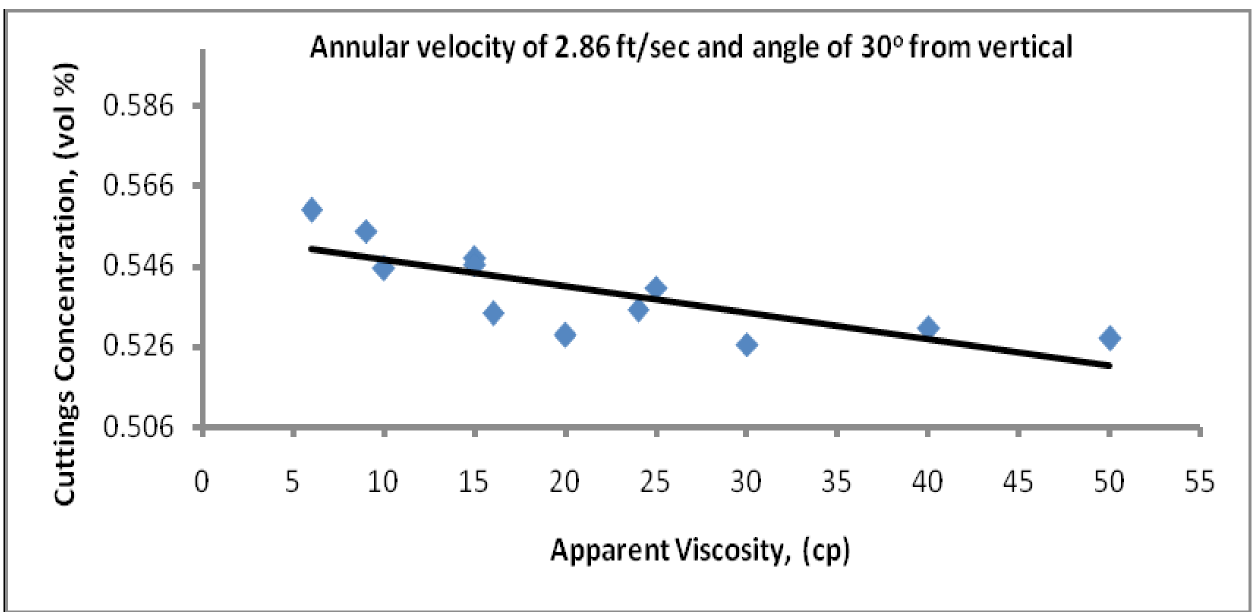

Fig. 2.5 (b): Annular cuttings concentration vs. Apparent viscosity for annular velocity of 2.86 ft/sec and angle of 30o from vertical.

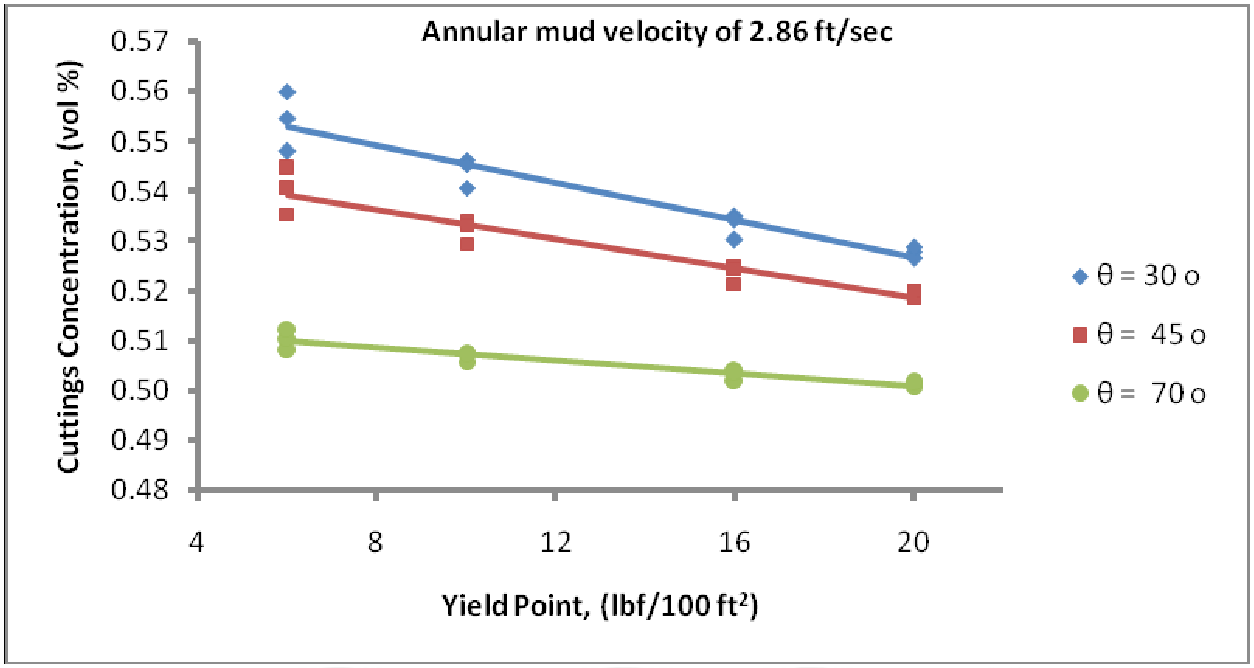

Fig. 2.6: Annular cuttings concentration vs. Yield point for annular velocity of 2.86 ft/sec

The combined effect of both yield point (YP) and plastic viscosity (PV) on the amount of cuttings concentration was also investigated in this study. Relatively high plastic viscosities considerably reduce the YP/PV ratio.

2.10 Summary, Conclusions and Recommendations

2.10.1 Summary

From this study, it can be deduced that the rheological parameters such as flow index, consistency index, yield point, plastic viscosity, and YP/PV ratio have tremendous impact on the transportation of cuttings. Therefore in order to ensure efficient cuttings transportation, each rheological parameter is equally important and should be considered. It has been observed that, an increase in both the apparent and effective viscosities helps in better sweep of the cuttings, the power law flow index should also not be very high while the power law consistency index should be increased.

The yield point and plastic viscosity values should all be high but done in such a way that they will result in low YP/PV ratios.

Again, whenever there is cuttings transport problem, flow rate should be increased to its limiting value for all ranges of inclinations, particularly in the range of higher angles. But when there is the occurrence of sliding-down effect of the cuttings during drilling, then this becomes critical for lower angles (30° - 45°).

2.10.2 Conclusions

The following conclusions were reached from this study:

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

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

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

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

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

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

vii. The effect of mud flow rate has great influence during hole cleaning in no vertical boreholes. Higher flow rates increases the critical annular velocity which in turn brings about decreasing cuttings concentration.

2.10.3 Recommendations for future Studies

The following suggestions are recommended for future work:

i. Investigation should be made into the effects of temperature and pressure on the rheology of drilling fluids for cuttings transportation in the drilling of no vertical boreholes.

ii. Field data should be used to carry out this same study to make conclusive statements on the impact of the power-law flow index, consistency index, yield point, plastic viscosity, and YP/PV ratio on cuttings transportation in no vertical boreholes.

iii. Develop advanced real-time rheology monitoring systems for directional wells.

iv. Explore machine learning models for predicting pressure fluctuations based on mud properties.

v. Conduct field-scale experiments on rheology variation under high-temperature/high-pressure (HTHP) conditions.

vi. Investigate interaction between rheology and MPD systems for deep water directional wells.

vii. Study Nano-enhanced drilling fluids to improve rheological stability.

2.11 Contributions to Knowledge

i. Provides a systematic analysis of how mud rheology affects pressure control specifically in directional wells.

ii. Establishes a framework for optimizing rheology to balance ECD, hole cleaning, and wellbore stability.

iii. Highlights interdependent effects of surge/swab pressures and rheological design.

iv. Identifies operational strategies and engineering controls suitable for complex well trajectories.

v. Extends the knowledge base for predictive drilling hydraulics modeling.

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