IMPROVED MODEL FOR CUTTINGS TRANSPORT IN HORIZONTAL AND VERTICAL WELLS

BY

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A PROJECT SUBMITTED TO THE DEPARTMENT OF PETROLEUM ENGINEERING,
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CERTIFICATION

This is to certify that this research project was carried out by DAVID OGHENETEGA SHADRACK of the Department of Petroleum Engineering at the University of Benin, Benin City, Edo State, Nigeria, under the supervision of PROF K.O BELLO.

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DEDICATION

This project is dedicated to Almighty God for His infinite mercy in seeing me through the project, my supervisor for its impact and perseverance, and to my family for their morale and financial support throughout my stay in the university of benin, department of petroleum engineering.

ACKNOWLEDGEMENT

I wish to express my appreciation of the efforts of my parents MR AND MRS DAVID IKPURU AND MY SIBLINGS for their moral and financial assistance, my supervisor, Professor K.O BELLO for his invaluable support and guidance towards the completion of this project, the HOD DR. IKPONMWOSA OHENHEN, and the entire lecturers and staff of the Department of Petroleum Engineering, University of Benin for their knowledge and impacts to my success so far, my coursemates who has supported in one way or the other, to my extended family for their support and selfless services towards my success, may GOD sufficiently bless you all.

ABSTRACT

Efficient cuttings transport and hole cleaning is very important for obtaining an effective drilling operation. In inclined and horizontal drilling, hole cleaning issues is a common and complex problem. This project explains the impact of various drilling parameters, and how they affect the required flow velocity and flow rate required for effective cuttings transport, cuttings transport is controlled by many variables such as well inclination angle, hole and drill-pipe diameter, rotation speed of drill pipe (RPM), drill-pipe eccentricity, rate of penetration (ROP), cuttings characteristics like cuttings size and porosity of bed and drilling fluids characteristics like flow rate, fluid velocity, flow regime, mud type and non - Newtonian mud rheology.

The following existing models were used which includes Larsen, Rubiandini, Moore, Hopkin, zeidler model, analysis was made on them based on the same parameters and prediction was obtained from the analysis, parameters used included ROP, mud weight, cutting size and mud rheology

The analysis shows that the larsens model gave the best slip velocity for lifting cuttings and effective hole cleaning.

The larsens model was therefore improved to get better results.

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CHAPTER ONE

INTRODUCTION

Transportation of cuttings is a mechanism that is a vital factor for a good drilling program. In directional and horizontal drilling, hole cleaning is a common and costly problem(Neff, 2005). Ineffective removal of cuttings can result in several problems, such as bit wear, slow drilling rate, increased ECD (which can lead to formation fracturing), high torque, drag, and in the worst case, the drill pipe can be stuck. If this type of situation is not handled properly, the problem can escalate to side tracking or loss of well, at worst.

Cuttings transport is controlled by many variables such as well inclination angle, hole and drill-pipe diameter, rotation speed of drill pipe (RPM), drill-pipe eccentricity, rate of penetration (ROP), cuttings characteristics like cuttings size and porosity of bed and drilling fluids characteristics like flow rate, fluid velocity, flow regime, mud type and non - Newtonian mud rheology. The key factors for optimizing hole cleaning is a result of good well planning, good drilling fluid properties, and good drilling experience(Mitchel and Miska, 2011):.

1.1 BACKGROUD OF THE STUDY

When drilling oil and gas wells, it is essential to transport the rock cuttings up to the surface. Wellbore instability in oil and gas well drilling is a collection of crushed rock particles from the wall of the well which mostly is accompanied with plugging of the formation by the crushed rock materials and also loss of circulation. Shales remain the most complex rock formation because of its silty nature which contributes about 80 – 85% of all drilling issues. Shale constitute about 60 – 75% of total rocks that are encountered during drilling operation. The wellbore instability can manifest in different ways and can be in the form of pressure exerted by the formation pores, strength of the rock, chemistry of the rock, hole pack off and excessive reaming. There are some factors which are controllable and include mud weight, inclination and azimuth of the wellbore. These controllable factors are dependent on mechanical behaviour of the rock formation. In drilling operations, the estimation of the pressure losses and the concentration of cuttings in the annulus are very complex due to the combination of drilling parameters interactions. The transport of cuttings and the efficiency of holes cleaning has been one of the biggest concerns of the oil and gas industry. In fact, a successful drilling program is the key to a productive and profitable oil and gas business. A successful drilling program is as a result of effective hole cleaning and a poor or inefficient hole cleaning results in accumulation of cuttings or cutting bed in the formation. This often results in reduced rate of penetration, increase in drilling cost, fracturing, increased in plastic viscosity of mud due to grinding of cuttings and stuck pipe problems. The cleaning of the holes is mainly done with a drilling fluid. The drilling fluid weight control is very important in wellbore instability management with the inclination angle of the well. Unfortunately, most drillers still depend on empirically derived Rule of Thumb instead of practicing the principles of rock mechanic and failure in formulating adequate drilling fluid weight(Rommetveit et al., 2003).

The circulating drilling fluid rising from the bottom of the well bore carries the cuttings toward the surface. Under the influence of gravity the cuttings tend to sink through the ascending fluid, but by circulating a sufficient volume of mud fast enough to overcome this effect, the cuttings are brought to the surface. The effectiveness of mud in removing the cuttings from the hole depends on several factors such as fluid viscoelastic properties, annular velocity, angle of inclination, drilled cuttings size and their shape.

As the demand for energy increases, harsh and extreme environments are explored for hydrocarbon, and deeper wells have been drilled to reach targets in formations with very high temperatures and pressures. To drill successfully, safely, and economically in such harsh environments, a drilling fluid whose properties remain stable when exposed to high temperatures and that can retard shale problems, ensuring the stability of the wellbore across the payzone, ensuring efficient cutting transport in different holes sections is required. Regarding their technical performance, oil-based mud (OBM) systems can be used successfully in such environments(Shadravan & Amani, 2012). However, oil-based drilling mud has its limitations: It is susceptible to contamination by water, there are fire risks, the rate of bit penetration is low, and most importantly, there is the risk of environmental impact. Arising from stringent environmental legislation, the current effort in the oil industry is geared towards the development of environmentally friendly fluids that could perform like oil-based muds. More so, industrial regulators are becoming stricter on the use of environmentally friendly drilling fluids. Even though water-based fluid systems are environmentally friendly, their instabilities when exposed to high temperatures remain a big challenge. High temperature affects the hydration of components, fluid loss, clay dispersion, and the degradation of additives in water-based fluids. One of the additives used in drilling fluids is polymer. The function of polymers in drilling muds is to provide viscosity, shale inhibition and fluid-loss control, and to prevent clay dispersion. They are selected for use based on the following: classification, strengths, weaknesses, molecular weight, and functionality. Synthetic polymers are stable at high temperatures, but are expensive, cause formation damage and generate high plastic viscosity. Conversely, biopolymers are non-toxic and less expensive and have less effect on formation damage(Mitchel and Miska, 2011).

The HPHT well is defined as the type of well in which the uninterrupted bottom hole temperature at depth of reservoir is higher than 300 °F which drills the porous formation with maximal pore pressure and exceeds the hydrostatic gradient of 0.8 psi/ft. Oil and gas industry has gained a significant attention worldwide due to the recent improvement in the drilling field where, most of the wells are being drilled, with different methods and techniques and drilling under HPHT condition is one of the interesting and demanding challenge for both researchers and drillers(Shadravan & Amani, 2012).

1.2 AIMS AND OBJECTIVES

The aims and objectives of the project are:

- ✓ To introduce, explain and in great details the empirical model focusing on the models of Larsen, Rubiandini,Hopkins,moore's and ziedler's model.
- ✓ To improve on an existing model to give better result in cutting transport mechanism.

1.3 STATEMENT OF PROBLEM

This project work involves drilling mud effects on the wellbore stability across the pay zones and the cutting transport in different holes sections in high pressure and high temperature wells.

At present, the biggest challenges for oil and gas exploration is to operate under conditions of HPHT as in the Niger delta, that can also be characterized as temperatures higher than 150 ° C (300 ° F) and bottom hole pressure greater than 10,000 psi. These extreme conditions, when experienced at the time of drilling operations, can cause massive fluid system problems and annular pressure limits while drilling (PWD), and also measure while drilling/logging while drilling (MWD/LWD) tools (Bland et al., 2006)

1.4 SCOPE OF STUDY

The scope of this project study basically, involves:

- ✓ Assuming pore/fracture pressure for analysis

- ✓ Designing a drilling mud program for meet HPHT wells consideration
- ✓ To optimize production rate by designing a drilling mud to prevent borehole instability and cutting transport problems.

1.5 RELEVANCE OF STUDY

- ✓ To provide fundamental information on the suitable drilling mud program to use in HPHT environments.
- ✓ To address the problems of drilling mud during drilling operations in HPHT environments.
- ✓ To acquire more knowledge on the field of research.

CHAPTER TWO

LITERATURE REVIEW

2.0 CUTTING TRANSPORT MECHANISM

Cutting transport is an important goal in drilling operation especially in horizontal and deviated wells since it can cause problems such as stuck pipe, circulation loss and high torgue and drag. he transportation of cuttings and efficient hole cleaning are indispensible in any drilling program. This is because a successful drilling operation is the key to a profitable business in the oil and gas sector. These have driven researchers into the study of cuttings transport and hole cleaning so as to predict hole cleaning efficiency of drilling fluids and optimize a drilling program.

A successful drilling program is as a result of an efficiently cleaned hole. On the other hand, a poor or inefficient hole cleaning implies accumulation of cuttings or formation of cuttings bed in the well. This often leads to decreased rate of penetration, increased cost of drilling, fractured formation, increased plastic viscosity of mud as a result of grinding of cuttings and stuck pipe. Hole cleaning is effected primarily with a drilling fluid. The function of a drilling fluid is chiefly the transportation of cuttings out of a drilled hole. Other major functions of a drilling fluid in a drilling program include: cooling and lubricating the bit and drill string, cleaning of the bottom of the hole, removal of cuttings from mud at the surface, minimizing of formation damage, controlling of formation pressures, hole integrity maintenance, improving of drilling rate, aiding of well logging operations, minimizing contamination problems, torque, drag, pipe sticking and corrosion of the drill string, casings and tubings.

Cuttings transport studies in vertical and deviated wells have been reported over the last four decades and are still on going.

2.1 TYPES OF DRILLING MUD

2.1.1 WATER-BASED DRILLING FLUID

Most wells are drilled with water-based drilling muds (WBMs). WBMs are made up of minerals, salts, and organic compounds. The base fluid is water. The additives in water-based muds include alkalis, salts, surfactants, organic polymers, barite, and clay. In addition, water-based drilling muds are also made of several metals. The toxic metals found in water-based muds include arsenic, nickel, chromium, barite, cadmium, copper, iron, lead, mercury and zinc (Neff et al., 1987). They also contain a substantial quantity of organic matter such as biopolymers, which are highly degradable and less toxic. The composition of water-based muds is as shown in Figure 2.1) (Neff, 2005). The mud additives are selected based on the type of formation to be drilled, formation lithology, and cost.

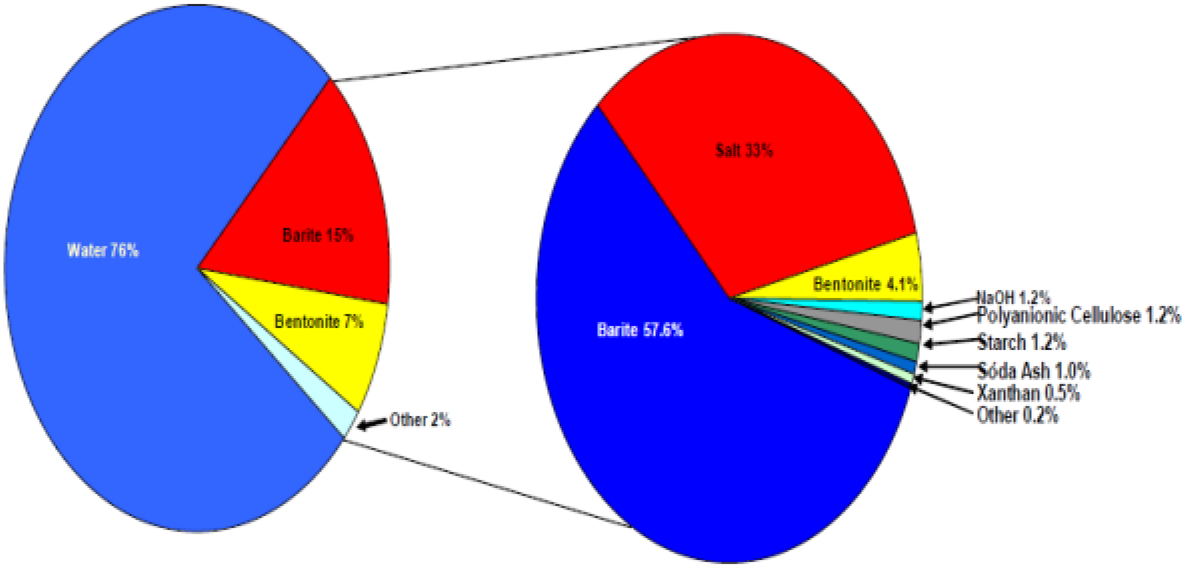


Figure 2. 1 A typical composition of water based drilling mud (Neff, 2005)

2.1.1.1 TYPES OF WATER-BASED MUDS

Water-based muds are categorized into dispersed and non-dispersed muds. The main difference between dispersed and non-dispersed muds is the lack of a dispersant. In the dispersed muds, chemical dispersant is used to disperse mud solids. Dispersants such as lignite and lignosulfonate are in use. Since the dispersants are acidic, they required an alkaline environment to function properly. The dispersants make it possible for clay to defloculate to control fluid losses. In the non-dispersed mud, dispersants are not added. One of the viscosifiers and fluid loss agents used in water based muds is bentonite. The pH of water-based mud is controlled with caustic soda (NaOH) while the density is controlled with weighting agents. There are two categories of dispersed muds: calcium-based and seawater muds. Since the non-dispersed drilling muds do not need high pH, a dispersant is not needed, but they are not as tolerant of solids and contamination as the dispersed muds. Polymers are usually used for fluid loss control and for viscosity. The polymers and other mud additives are very susceptible to contaminations from produced gases and fluids (Young, 1993). Water-based fluids are classified as follows (Mitchel and Miska, 2011):

- Inhibitive
- Non-inhibitive
- Polymer

There are no specific ions - sodium, calcium, and potassium - in non-inhibitive fluids, but inhibitive fluids have these ions. Since non-inhibitive fluids do not have these ions, they do not significantly inhibit clay swelling. Non-inhibitive fluids are made up of clay from the formation to be drilled or bentonite and caustic soda or lime, deflocculant or dispersants or both are also added to non-inhibitive fluids. Lignites, lignosulfonates, or phosphates are the dispersants usually used in non-inhibitive fluids, which are generally spud muds (Amoco Production Company,1994). Inhibited water-based systems minimize water wetting of the rock pores, and do not contain chemical dispersants (thinners) as well as inhibitive ions. But they are made up of native water. The cations such as (Na^+), (Ca^{++}) and (K^+) in inhibited water-based systems reduce clay swelling. The inhibitive drilling fluid system are usually used to drill reactive shale formation and sandstone formations containing reactive clays. High cost of disposal is a major disadvantage of using an inhibitive fluid since the source of the cation is usually a salt. Polymers are used to provide viscosity, to control fluid loss, and to deflocculate or encapsulate solids in drilling fluids. Polymers can remain stable up to 400 ^{0}F and the presence of solids poses a big challenge to the use of polymer mud systems. To enhance shale inhibition, potassium chloride is used as the brine for polymer mud system. The inhibitive properties of polymer fluids can further be improved by using glycol and amine-based inhibitors (PetroWiki, 2015). In this present study, polymer-based muds are designed for high temperature operations and for shale inhibition.

INHIBITIVE FLUIDS

These types significantly delay shale swelling and accomplish cation inhibition typically, sodium (Na+), potassium (K+) and calcium (Ca_2 +) are called inhibitive. Ca_2+ or K+ generally, or both in combination, provide the best inhibition of clay. Generally, they used to drill hydratable, reactive clays and sands that contain hydratable clays(Mitchel and Miska, 2011):

NON-INHIBITIVE FLUIDS

They do not substantially cure the problem of clay swelling and usually they made up of bentonites with caustic soda or some lime. They may compose of deflocculants like lignosulfonates, lignite, or phosphates.

POLYMER FLUIDS

They depend on macromolecules either both, with or without interactions of clay-mineral to provide properties of mud, and that are extremely diverse in their application. They, depending on whether an inhibitive cation is used, can be inhibitive or non-inhibitive Polymers may be used to increase fluid viscosity, to control filtration, to defloculate solids or to encapsulate solids. Polymer systems' thermal stability can range up to 400 ° F.

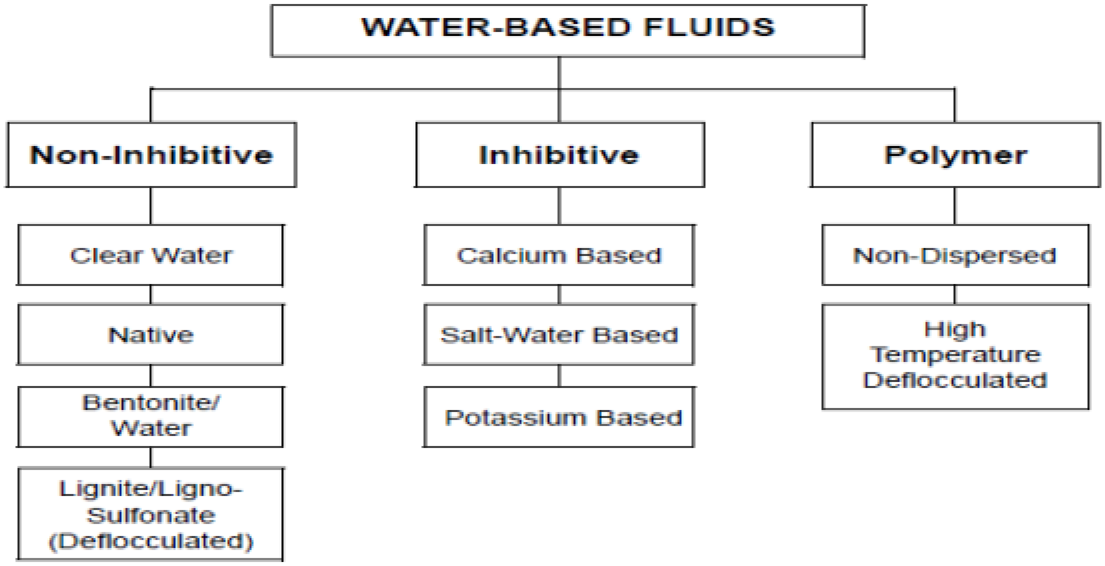


Figure 2. 2 Water- Based drilling fluids (Amoco Production Company, 1994)

2.1.1.2 DISADVANTAGES OF WATER- BASED MUD

The major disadvantages of WBMs are as follows:

1. Unwanted increase in density from salt in a formation

2. Causes formation damage.

3. Causes clay disintegration and dispersion

4. Not effective in sensitive shale formation

5. Causes corrosion

2.1.1.3 THE ADVANTAGES OF WBMS

The major advantages of WBMs are as follows:

1. It is easy to handle, inexpensive, and cost effective.

2. Low toxicity on the environment.

3. It is readily available.

4. High rate of penetration.

2.1.1.4 EFFECTS OF WATER-BASED MUDS ON THE ENVIRONMENT

Arising from stringent environmental legislation, the current effort in the oil industry is geared towards the development of environmentally friendly fluids that could perform like oil muds with respect to toxicity, performance, efficiency, and cost. Consequently, various studies have been undertaken to design high performance water-based muds(Mitchel and Miska, 2011).

. One of the drilling fluid additives that make the performance of water-based muds approach that of oil-based muds are salts. In the present study the salts used for drilling mud formulation are potassium formate and sodium erythorbate. Soluble silicates, which are salts, are commonly used to improve the properties of water-based muds. The mud formulation performed much better than conventional water-based muds (WBMs), and demonstrated excellent cuttings and well-bore stabilising capacity. They noted that OBMs and synthetics should be replaced by improved WBMs. However, the rheological properties of the mud system were adversely affected by temperature. In addition, silicates can cause formation damage, and it is difficult to control the rheological properties of drilling mud when using silicate-based mud system.

2.1.2 OIL BASE MUDS

The fluid formulation consists of suspended solid particles in oil. Water may added to oil to make emulsion, the oil is considered as continuous phase and water represent the dispersed phase.These systems are usually more expensive and require a higher level of environmental assessment.

However, the most oil-based muds (OBM) common uses are, drilling reactive formations of shale and enhances wellbore stability. These fluid types have various applications, such as wells under HPHT conditions. They reduce damage to the formation, have good lubricity and help to inhibit clay hydration (Amoco, 1994). Such mud types also have the advantage of being reconditioned and reusable. The cost of a multi-well program can then be compared by the use of a water-based mud system.

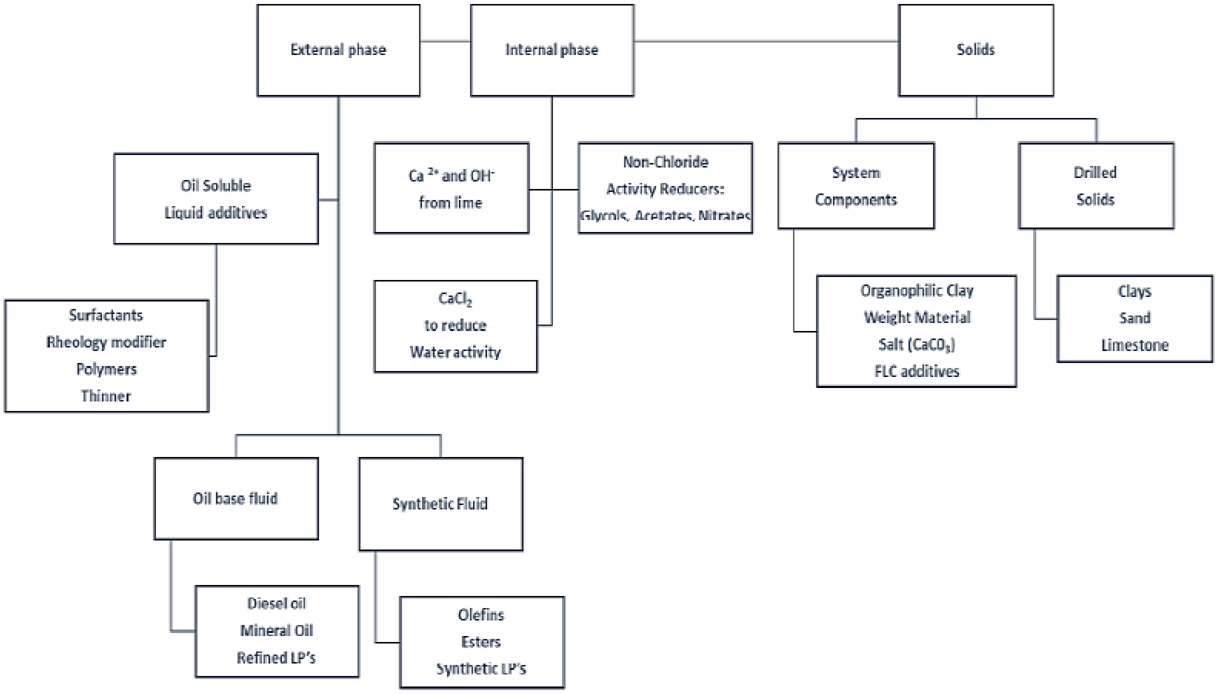


Figure 2. 3 Types of Invert-Emulsion (Dn et al., 2005)

2.2 RHEOLOGICAL MODELS

Newtonian model, the Bingham plastic model, the Power-Law or Ostwalde-de Waele model, and the Herschel-Bulkley model are used to approximate fluid behaviour (Mitchel and Miska, 2011).

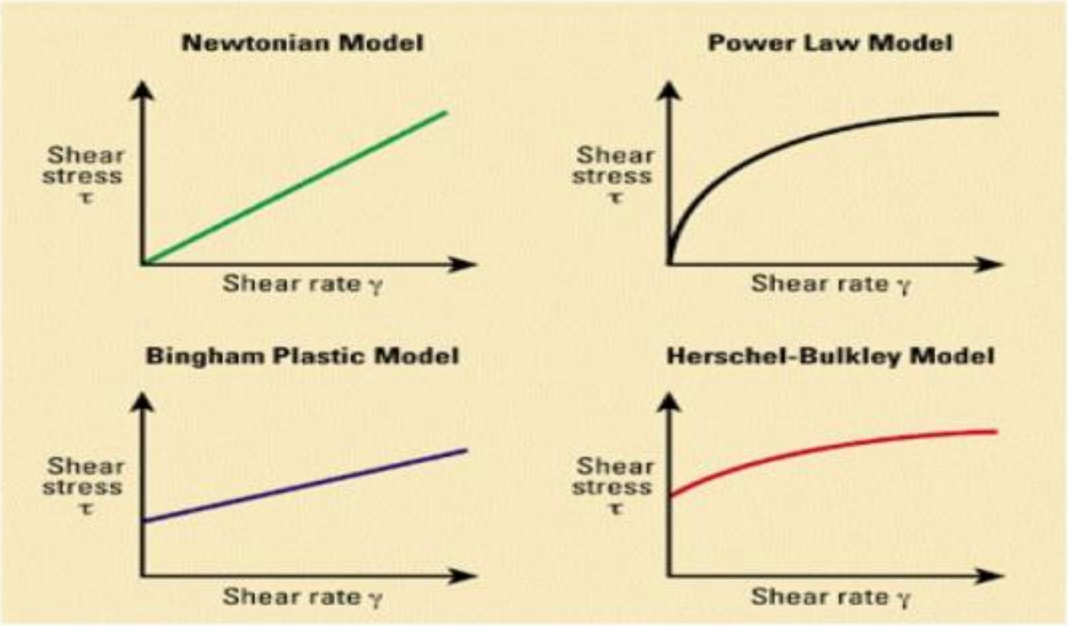


Figure 2. 4 Rheological Models (Ochoa, 2006)

2.3 WHAT IS HPHT WELL?

The HPHT well is defined as; it is a type of well in which the uninterrupted bottom hole temperature at depth of reservoir is higher than 300 °F which drills the porous formation with maximal pore pressure and exceeds the hydrostatic gradient of 0.8 psi/ft (Shows an EMW of 1.85 SG) or BOP with working pressure rate above 10M. (Shadravan & Amani, 2012).

Oil and gas industry has gained a significant attention worldwide due to the recent improvement in the drilling field where, most of the wells are being drilled with different methods and techniques and drilling under HPHT condition is one of the interesting and demanding challenge for both researchers and drillers. In addition, oil sector studies shows that approximately around 100,000 wells drilled globally in year 2012, and recent studies have made the estimates more accurate, about 1.5 percent should be categorized as HPHT. Even though these wells are comparatively small, they often represent considerable resources and mostly exist in regions in which exploration is ongoing in new horizons(Smithson, 2016).

2.3.1 BACKGROUND OF HPHT WELLS

In a broad range of important services, including power generation, transport fuels, and consumer products, oil and gas continues to be used. Driven by increase in the population and consumer purchasing power in developing economies, overall global energy consumption of oil and gas (Douglas Westwood, 2014) is expected to rise by 34%, from today to 2030.

The Organization for Economic Cooperation and Development (OECD) estimates that demand has been growing speedily since 1990 with higher oil and gas prices in recent years. This is because of a gradual slow down trend in the search for new oil and gas reservoirs, and the market is heading towards high risks and more challenging conditions that meet demand of global energy (Bland et al., 2006). This demand is mainly recognized for the development of oil and gas fields particularly focusing on Complex subsea /deep-water and ultra-deep-water.

The extreme situations may be categorized as;

(I) Deepwater wells and
(ii) Wells of high - Pressure and temperature because these types of wells need a combination of various well planning and special tool specifications for exploration.

At present, the biggest challenges for oil and gas exploration is to operate under conditions of HPHT , that can also be characterized as temperatures higher than 150 ° C (300 ° F) and bottom hole pressure greater than 69 MPa (10,000 psi) (Joshi & Lee, 2013). These extreme conditions, when experienced at the time of drilling operations, cause massive fluid system problems and annular pressure limits while drilling (PWD), and also measure while drilling/logging while drilling (MWD/LWD) tools (Bland et al., 2006).

The growth of the petroleum industry emerges from the continuous discovery of hydrocarbons in new and unexplored areas. In terms of temperatures, pressure and depths, the search for hydrocarbons has become more challenging in extreme environments, contractors and service companies are pushing forward with new HPHT drilling technologies and innovations. A variety of innovations and developments are ongoing in pipeline to give relief to the industries in order to access hydrocarbons that once were considered too complicated to access in the search of natural gas and oil, oil industry has spent a great deal and recently reached to an agreement: there is no production of undiscovered fields in offshore environments. Thus, according to Simmons, the new solutions and developments to deep HPHT well drilling is important to achieve the engineering requirements while keeping the projects economically feasible. Key aspects well drilling above 20,000 ft, sub-salt drilling, very short drilling windows, operational difficulties such as circulation loss, stuck pipe and well-control problems are much more likely while drilling in HPHT environments. (Joshi & Lee, 2013). The most specific HPHT definition is that when the pressure is greater than 10 000 psi (690 bars) and the temperature is higher than 300 ° F (149 ° C). As per research, HPHT will be defined in the near future when the pressure exceeds 15 000 psi and the temperature exceeds 300 ° F. New categories were therefore developed to help define operating conditions of HPHT, stable operating systems and technological gaps.

2.3.2 WELL PLANNING IN HPHT CONDITION

Whereas High Pressure High Temperature (HPHT) wells compensate just 1-3 % of the total wells being drilled, this practice is worldwide and has received significant attention. The development of some of these reservoirs primarily depends on the capacity of service companies to drill, analyze and complete wells under HPHT conditions. Recently, demands for the provision of HPHT-enabled and effective equipment from directional drilling service companies have appeared in a number of drilling and assessment tenders in different regions of the world. Operating companies are familiar of the challenges involved with durability of downhole equipment under HPHT scenarios. Reliability of drilling mud and downhole equipment in HPHT wells remains a significant challenge for the oil and gas sector. The upstream service companies of gas and oil are involved in the production of wells are impacted by reliability problems.

2.3.3 HPHT DRILLING CHALLENGES

While dealing with an HPHT well, we have several challenges; one is because of the narrow margin between the pressure of the fracture and the pressure of the pore which requires extensive control of the BHP. The effects of temperature and pressure in a HPHT condition can often be very much challenging. HPHT drilling technological principles are effective tools for designing, preparing and construction of HPHT wells. Formation pressure forecast, fracture pressure measurement, depth of casing setting, rheological performances of drilling fluid, hydraulics, selection of bit and cementing programs all must be thoroughly adjusted for HPHT drilling conditions. In addition, unconventional drilling methods like casing-drilling and managed pressure drilling could be used to reduce non - productive time (NPT) and result in safer drilling. Daunting difficulties such as; limited assessment capability, low ROP in production areas, well control and non -productive time have been of main consideration for drillers in the design and construction of HPHT wells.

2.3.4 TEMPERATURE EFFECT

In high temperature wells, we have effect of temperature, probably as a result of temperature, the density of the drilling fluid changes in the depth of a well. This effect of High temperatures will reduce the mud density, however if the well has been influenced by high temperatures, the effective mud weight of the downhole will be smaller than what you see on the surface. In certain situations, the temperature effect can be easily mixed with a kick event and as a result increase in the amount of mud on the surface. This could be hazardous during drilling operations as we will get an appropriate mud weight down into the well which is smaller than what we see on the ground, which indicates that the risk of an underbalance condition is greater. If we have an underbalanced at drilling time, in the wellbore the formation fluids will begin flowing, in order to prevent kicks, the mud weight of efficient surface can be adjusted to obtain the required effective weight of mud down the hole. While we have static conditions into a well the temperature of mud reaches the geothermal temperature of the well, the drilling mud temperature of the will change quickly depends on the operation. As we begin to flow into the well, cold mud come out of the drill string reaches the annulus where warm mud flows into the top of the annulus. This results in a rapid change in density and rheology of mud at various locations in the well, resulting the change in ECDs and changes in mud volumes in the surface (Aadnoy, 2006).

2.3.5 PRESSURE EFFECTS

For HPHT wells, hydrostatic pressure differences are greater than in normal wells for drilling. It is because of variations in density of mud caused by pressures and temperatures. High pressure raises the mud density and the downhole mud weight is greater than that measured on the surface, if the well is dominated by higher pressure.

Variations in pressure in HPHT wells are increased compared with traditional wells.

There are some explanations for that; (Rommetveit et al., 2003).

1. As the mud density increases the hydrostatic pressure will change more.

2. Changes in frictional pressure may occur, due to variations in wellbore rheology.

3. Frictional pressure would be higher. Changes in rheology cause the flow regime to a transition from laminar to turbulent flow.

4. More critical pressure by surge and the swab.

5. Mud rheology is based on the history of the shear. During circulation, breaking gels induce rapid peak pressure in the lower hole (Rommetveit et al., 2003).

We often encounter pressure effects as a result of rheology change, first we experience frictional variations due to temperature effects causing rheology variations and even changes in rheology can lead to transitions within flow schemes that lead to increased frictional pressure losses.

2.3.6 SAFETY IN HPHT WELLS

Control of Pressure and temperature is the most difficult safety issue in HPHT reservoirs. All operations, including drilling, completion of well, exposes the equipment to a difficult operating condition. Operating conditions often exceed the upper limit of hardware requirements thus improving the risk of failure of tool or metal fatigue resulting in a loss of rig time, cost overruns and increased cost of replacement. Standard operating procedures (SOPs) and appropriate mud design must be defined and properly enforced to guarantee safe and effective operations. Quality control measures should be developed for all products and equipment so as not to exceed operating pressure and temperature limits.

2.3.7 WELLBORE INSTABILITY IN HTHP WELLS

Wellbore Instability has major effects during drilling under high temperature and pressure conditions, as instability of wellbore is a normal feature of inadequate mechanical stress and physiochemical interfaces, and pressure generated while material and surface support is exposed during the Wellbore Instability (WI), well drilling phase is recognized when the diameter of hole is marked different from size of bit and the hole doesn’t keep its structural integrity. Concisely, an over-gauge or under-gauge hole means instability of wellbore. In addition for oil and gas wells to be successfully drilled, it is crucial to formulate mud of a sufficient mud weight to preserve the stability of the hole, to avoid the influx of formation fluid in the wellbore and to reduce the loss of mud.

Wellbore instability is becoming a significant issue for horizontal and extended reach wells, particularly by pushing into the fully open side hole section and in certain scenarios by cap rocks of shale, a buildup section of open hole .More recently drilling advancements, such as under-balanced drilling methods, high-pressure jet drilling, horizontal wells reentry and several laterals from the a single horizontal or vertical well often eventually lead to difficult stability issues of wellbore.

2.3.7.1 CAUSES OF WELLBORE INSTABILITY IN HPHT WELLS

Different factors likewise and reservoir properties and drilling mud chemistry influence the wellbore instability in deep-water gas well. Properties of Drilling fluid might be utilized to directly influence stabilization of wellbores. Physicochemical interaction with both the formation, Filtration behavior vs density of mud are the drilling fluids properties which may be optimized to effect stability of wellbore. There were also reported problems of wellbore instability during drilling in naturally fractured formations. Many of the observed formations possess micro-scale and macro bedding planes and natural fracture networks which diminish the compressive strength of both the formation and the productivity of the formation matrices (Fekete et al., 2015).

2.3.7.2 PREVENTION OF WELLBORE-INSTABILITY

Total borehole instability prevention is unreasonable, primarily because the rock could never be returned to its original conditions. The drilling engineer however diminish the troubles of borehole instability by implementing good practice.

The following practices comprise.

- ✓ Selection and maintenance of suitable mud-weight
- ✓ The proper hydraulics use to regulate the equivalent circulation density (ECD)
- ✓ Proper selection of hole-trajectories

The application of borehole fluid compatible with the drilled formation, The following are extra field practices:

- ✓ Use of offset-well data (use of the curve)
- ✓ change in the monitoring trend (circulating pressure, torque, drag, fill-in during tripping)
- ✓ Sharing and collaborating information (Pašić et al., 2007).

DRILLING FLUID/MUD PROPERTIES	REQUIRE PERFORMANCE IN HPHT WELLS
Plastic viscosity	As low as reasonably possible to minimize equivalent circulating density (ECD)

Yield stress and gels	Sufficient to prevent sag, but not so high as to cause gelation, or high surge and swab pressures.
HPHT fluid loss	As low as reasonably possible to prevent formation damage and risk of differential sticking.
HPHT rheology	Predictable in order to control sag, gelation and ECD
Compressibility	Must be known to estimate downhole pressures and ECD
Stability to contaminant	Stable in the presence of gas, brine and cement
Gas solubility	Needed for accurate kick detection, designing and modelling
Stability to aging	Properties do not change over time under either static or dynamic conditions
Solids tolerance	Properties insensitive to drilling solids
Weighting	Must be able to be weighted up rapidly if a kick is taken

Table 1.0: Effect of several key drilling mud/fluid properties on mud performance in HPHT wells.

2.4 FLOW REGIMES

$\boldsymbol{\tau}=\frac{F}{A}$

The flow regime has a direct impact on the cuttings transport, and the flow can be either laminar or turbulent. The flow regime is dependent on the fluid velocity, size, and shape of the annulus, fluid density, and viscosity[38]. The fluid flow region between laminar and turbulent is known as a transition region. In this region, the fluid has both laminar and turbulent characteristics. During drilling, rotation of drill-pipe can create a turbulent flow. When flow velocity is low or when the fluid has high viscosity, it creates a laminar flow. On contrary, the turbulent flow arises when the flow velocity is high or when the fluid has low viscosity. In addition, drill pipe or wall roughness will increase the flow turbulence. In general, it requires a higher pump pressure to transport fluid in turbulent flow than in laminar flow.

The transition region between laminar and turbulent flow is controlled by viscous forces and inertial forces in the flow. In the laminar flow, the viscous forces are dominant, while in the turbulent flow the inertial forces are most important. The ratio of inertial forces to viscous forces is known as the Reynolds number. The dimensionless Reynolds number in the annulus is defined as follows[38]:

$$\boldsymbol{Re}=\frac{(\mathbf{Dhole}-\mathbf{Dpipe})*\mathbf{V}*\boldsymbol{\rho}}{\boldsymbol{\mu}}$$

The transition from laminar to turbulent flow regime occurs at a critical flow velocity. For a typical drilling fluid, the Reynolds number in the transition region is varying between 2000 and 4000.

Shear Stress

Shear stress is the force required to maintain a particular rate of fluid flow, and is measured as a force per unit area. The shear stress is defined as follows:

$$\boldsymbol{\tau}=\frac{F}{A} \qquad 2.1$$

In order to calculate shear stress in the annulus, the force that pushes fluid through annulus and the area of the fluid surface in the annulus is calculated as follows:

$$\boldsymbol{F} = \boldsymbol{P} * \boldsymbol{\pi} \frac{Dhole^2 - Dpipe^2}{4} \qquad \mathbf{2.2}$$

Equation for surface area in the annulus subjected to stress is defined by following:

$$\boldsymbol{A} = \boldsymbol{\pi} * \boldsymbol{L} \; [\boldsymbol{Dhole} + \boldsymbol{Dpipe}] \qquad 2.3$$

With use of equations in the annulus.

Shear Rate

Shear rate is defined as the velocity gradient measured across the diameter of an annulus. The velocity gradient can be expressed as the rate of velocity changes with distance from hole wall.

Shear rate can be expressed mathematically as follows:

$$\boldsymbol{\gamma} = \frac{\Delta V}{\Delta r} \qquad 2.4$$

The shear rate at the annulus wall for a Newtonian fluid is defined as follows:

$$\boldsymbol{\gamma a} = \frac{12 * Va}{\text{Dhole} - \text{Dpipe}} \qquad 2.5$$

The average velocity in the annulus (Va) is expressed as follows;

$$\boldsymbol{Va} = \frac{4Q}{\pi[Dhole^2 - Dpipe^2]} \qquad 2.6$$

During drilling, density of drilled cuttings is higher than the drilling-fluid, and it leads to cuttings particle settling in a drilling fluid. The fluid that surrounds particles is subjected to a shear rate, which is known as settling shear rate (γs):

$$\boldsymbol{\gamma s}=\frac{\mathbf{12*Vs}}{\mathbf{Dcuttings}} \qquad 2.7$$

Viscosity and Apparent Viscosity

The viscosity is defined as the ratio of shear stress to shear rate38. Unit for the viscosity is dyne-s/cm2, which is represented as Poise (P). 1 Poise represents a relatively high viscosity for most fluids, and therefore unit centi-Poise (cP) is more often used.

The equation for viscosity is defined as follows:

$$\boldsymbol{\mu}=\frac{\boldsymbol{\tau}}{\boldsymbol{\gamma}} \qquad 2.8$$

Viscosity varies for most drilling fluids, and it varies with shear rate.

Apparent viscosity is defined as a viscosity of a fluid measured at a given shear rate at a fixed temperature39. In addition, apparent viscosity is a rheological property calculated from rheometer reading performed on drilling fluid. In order for a viscosity measurement to be meaningful, the shear rate must be stated or defined.

The apparent viscosity is expressed as:

$$\boldsymbol{\mu a}=\boldsymbol{pv}+\frac{\mathbf{5}\boldsymbol{YP}(\boldsymbol{Dhole}-\boldsymbol{Dpipe})}{\boldsymbol{Vcrit}} \qquad 2.9$$

2.5 DIFFERENT CUTTING TRANSPORT MODELS ANALYSED

2.5.1 LARSEN’S MODEL

Larsen focused on cuttings size, angle of inclination and mud weight, and therefore were able to develop empirical correlations for these variables. In addition, a design model was developed to predict the critical transport fluid velocity, equivalent slip velocity, and critical velocity.

Larsen’s equivalent slip velocity and Critical Transport Fluid Velocity (CTFV)

Larsen defined equivalent slip velocity as a flow velocity difference between cuttings and drilling fluid. Equation for equivalent slip velocity [ESV] (ft/sec) is defined as correction factors for inclination angle, cuttings size, and mud weight multiplied by uncorrected equivalent slip velocity $\underset{\cdot}{V}\ slip$, and is shown as follows:

$$Vslip = \underset{\cdot}{V}\ slip * Cang * Csize * Cmw \tag{2.10}$$

Larsen and his coworkers defined critical transport fluid velocity (CTFV) as the minimum fluid velocity that is required for keeping a continuously upward movement of the cuttings during circulation. That means that at this velocity or higher, the hole cleaning will be sufficient enough so that no cuttings will accumulate in the lower part of the wellbore.

The equation for critical transport fluid velocity (CTFV or Vcrit) is the sum of cuttings transport velocity (CTV or Vcut) and slip velocity (Vslip):

$$Vcrit = Vcut + Vslip \tag{2.11}$$

Cuttings transport velocity (CTV or Vcut) can be expressed through a simple mass balance equation:

Mass generated by drill bit= Mass transported by Mud

$$\rho cut * Qinj = Vcut * Aopen * Cconc{-}ft * \rho cut \tag{2.12}$$

Cuttings transport velocity in the equation above is calculated by:

$$\boldsymbol{Vcut} = \frac{\mathrm{Qin}}{\mathrm{Aopen} * \mathrm{Cconc} - \mathrm{f}} \qquad 2.13$$

In order to convert volumetric injection rate (Qinj) to ROP, the following equation has been used:

$$\boldsymbol{ROP}.\ (\frac{ft}{hrs}) = \boldsymbol{Qinj\ .\ ft\ sec} \ / * .\ \mathbf{3600}\boldsymbol{sec}\ \mathbf{1}\boldsymbol{hrs}\ / \ \mathbf{1}\ \boldsymbol{Ahole\ ft}\ \mathbf{2} \qquad 2.14$$

By substituting volumetric injection ratio (Qinj), with ROP, it is possible to calculate cuttings transport velocity considering ROP, drill-pipe, hole diameter, and fractional cuttings concentration:

$$\boldsymbol{Vcut} = \frac{\mathrm{ROP}}{36\left[\left(1 - \frac{Apipe}{Ahole}\right)\right] Cconc.} \qquad 2.15$$

Or

$$\boldsymbol{Vcut} = \frac{ROP}{36\left[\left(1 - \frac{Dpipe^2}{Dhole^2}\right)\right]} \qquad 2.16$$

Uncorrected equivalent slip velocity $\underset{.}{V}\ \boldsymbol{slip}$ in equation above, based on experimental data, can be calculated as follows:

$$\underset{.}{V}\ \boldsymbol{slip} = \mathbf{0.00516} * \boldsymbol{\mu a} + \mathbf{3.006}\ \boldsymbol{For\ \mu a} < 53\ \boldsymbol{cp} \qquad 2.17$$

$$\underset{.}{V}\ \boldsymbol{slip} = \mathbf{0.02554} * (\boldsymbol{\mu a} - \mathbf{53}) + \mathbf{3.28}\ \boldsymbol{For\ \mu a} > 53\ cp \qquad 2.18$$

The apparent viscosity (μa) in equations above is calculated by:

$$\boldsymbol{\mu a} = \boldsymbol{pv} + \frac{\mathrm{5YP(Dhole - Dpipe)}}{\mathrm{Vcrit}} \qquad 2.19$$

Larsen’s correction factor for inclination

Random angles, namely 55°, 65°, 75°, and 90°, were selected to define the angle of inclination correction factor. Then an average of these angles was found and mean of critical transport flow velocity (CTFV) for these individual angles was calculated. Thus, the angle of inclination correction factor was defined by dividing CTFV mean by angle average.

Correction factor for inclination is calculated by the following expression:

$$Cang=0.0342\theta ang-0.000233\theta ang2-0.213 \qquad 2.20$$

The cuttings size correction factor is expressed by:

$$Csize=-1.04*DCuttings+1.286 \qquad 2.21$$

The correction factor for mud weight is expressed by:

$$Cmw=1-0.(\rho m-8,7)\ \rho m>8.7 \qquad 2.22$$

$$Cmw=1\ \rho m<8.7 \qquad 2.23$$

Larsen’s correction factor for sub-critical fluid flow

Larsen indicated that for any flow velocity that was below critical transport fluid velocity, cuttings would start to accumulate in the wellbore. This fluid velocity was called sub-critical fluid flow. They assumed the velocity in the open area above the accumulation area or above cuttings bed to be equal to critical transport fluid velocity (CTFV).

By neglecting flow through the cuttings bed, the area occupied by cuttings bed is equal to the total annulus area minus the open area above cuttings bed.

Correction factor for cutting concentration at sub-critical fluid flow can be presented as:

$$Cbed=0,97-0,00231*\mu a \qquad 2.24$$

The equation above indicates that cuttings bed concentration is dependent on apparent viscosity.

Where;

Aann = Area of annulus (ft2), (m2)

Abed = Area of cuttings bed (ft2), (m2)

Aopen = Area open to flow above the cuttings bed, (ft2), (m2)

Cang = Correction factor for inclination (dimensionless)

Cconc = Fractional cuttings concentration, by volume, at CTFV (%)

Cconc-ft = Fractional cuttings concentration for a stationary bed corrected for viscosity (dimentionless)

Cmw = Correction factor for mud density (dimensionless)

Csize = Correction factor for cuttings size (dimensionless)

Dhole = Hole diameter (inch), (m)

Dpipe = Drill-pipe diameter (inch), (m)

PV = Plastic viscosity (cP), (Pa*s)

Qinj = Volumetric injection rate of cuttings, (ft3/sec), (m3/sec)

ROP = Rate of penetration (ft/hrs), (m/hrs)

Vcrit = Critical velocity (CTFV), (ft/sec), (m/sec)

Vcut = Cuttings transport velocity (CTV), (ft/sec), (m/sec)

Vslip = ESV corrected for angl, cuttings size and mud weight (ft/sec), (m/sec)

$\boldsymbol{V\ slip}$ = Correction factor for slip velocity (dimensionless)

YP = Yield point (lbf/100 ft2), (Pa)

μ a= Apparent viscosity (cP), (Pa*s)

$\boldsymbol{\theta ang}$= Angleof inclination of wellbore from vertical (degrees)

ρcut = Density of cuttings, (lbm/gal), (kg/m3)

ρm = Density of drilling fluid, (lbm/gal), (kg/m3)

2.5.2 RUDI RUBIANDINI’S AND MOORE’S MODELS

The model was based on Moore model for vertical wellbore, Larsen et al. empirical model and Peden et al. experimental data.

Rubiandini claimed that hole-cleaning problems could be mastered by defining the minimum mud rate that had a capability to clean the drilling wellbore. He expressed the minimum mud rate as a sum of the slip velocity and velocity of the fallen cuttings, similar to Larsen. The cuttings velocity was dependent on the wellbore geometry and magnitude of ROP.

Rubiandini believed that mud weight, inclination angle, and RPM were major factors affecting cuttings transport mechanisms. Therefore, corrections factor of these parameters played a main role in the model he proposed.

Rubiandini introduced slip velocity and correction factor for mud weight and angle of inclination. In his research, Rubiandini modified the Moore‟s slip velocity that was applicable for vertical wellbore in such way so that it would be possible to use in the inclined-until-horizontal wells. Rubiandini presented a new equation for determination of the mud minimum rate that was necessary to lift the cuttings in the inclined-until-horizontal wellbore.

Rubiandini cuttings lifting equation

The angle correction factor was obtained by using Cartesian dimensionless plotting between slip velocity (Vslip) and inclination, based on Larsen‟s and Peden‟s data, and was expressed as:

$\theta \leq 45^0$

$\boldsymbol{Ci}=[1+\frac{2\theta}{45}]$ 2.25

$\theta \geq 45^0$

$\boldsymbol{Ci}=2$

Based on the dimensionless plotting between slip velocity and inclination, for varied mud density, the following density factor was found:

$$\boldsymbol{Cmw} = \frac{3+\rho m}{15} \qquad 2.26$$

The RPM correction factor was determined from dimensionless plotting between slip velocity (Vs) and inclination, based on Peden‟s method, for varied RPM by linear regression and was defined as:

$$\boldsymbol{CRPM}=\frac{600-RPM}{600} \qquad 2.27$$

Minimum velocity for vertical or horizontal well was written as:

$$\boldsymbol{Vmin}=\boldsymbol{Vcut}+[\mathbf{1}+\boldsymbol{Ci}*\boldsymbol{Cmw}*\boldsymbol{CRPM}]*\boldsymbol{Vslip} \qquad 2.28$$

In the equation above, a cuttings velocity equation (Vcut) was found using the same as in the Larsen‟s model.

Finally, Rubiandini‟s minimum velocity for a well inclination below 45°degrees was defined as:

For $\theta \leq 45^0$:

$$\boldsymbol{Vmin}=\boldsymbol{Vcrit}=\boldsymbol{Vcut}+[\mathbf{1}+\frac{\boldsymbol{\theta}*(\mathbf{600}-\boldsymbol{RPM})*(\mathbf{3}+\boldsymbol{\rho m})}{\mathbf{202500}}] \qquad 2.29$$

Rubiandini‟s minimum velocity for a well inclination above 45°degrees was defined as:

For $\theta \geq 45^0$:

$$\boldsymbol{Vmin}=\boldsymbol{Vcrit}=\boldsymbol{Vcut}+[\mathbf{1}+\frac{(\mathbf{600}-\boldsymbol{RPM})*(\mathbf{3}+\boldsymbol{\rho m})}{\mathbf{4500}}] \qquad 2.30$$

Rubiandini‟s model is applied for inclination angle between 0° and 90° degrees. At 0° degrees, Rubiandini‟s model corresponds to Moore‟s model for vertical wellbore. Minimum flow velocity defined by Rubiandini showed gradual increase at the inclination interval between 0° and 45° degrees. However, in the inclination angle interval between 45° and 90° degrees, Rubiandini‟s minimum flow velocity is a constant value. Minimum flow velocity based on Larsen et al.

calculations and Peden‟s experiment have smaller value compared to Rubiandini‟s minimum flow velocity for inclination less than 45° degrees.

2.5.3 HOPKINS METHOD -CRITICAL FLOW RATE

Hopkins 1995 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.

$$V_s = \frac{(\rho_s - \rho_m)^{0.667} * 175 * d_c}{\rho_m{}^{0.333} * \mu\hat{}0.333} \qquad 2.31$$

Where, ρ_s is density of solid, ρ_m is density of mud, dc = 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,

$$\text{FMW} = 2.117 - 0.1648 * \rho_m + 0.003681 * \rho_m^2 \qquad 2.32$$

$$\mathrm{V_s} = \mathrm{FMW} * \mathrm{V_{sv}} \qquad 2.33$$

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

$$V_{min} = V_s \, cos\theta + V_2 \sin\theta \qquad 2.34$$

Step 4: In Step 3, V2 is calculated using formula

$V_2 = C * [(\frac{\rho_s - \rho_m}{\rho_m}) g^3 (\frac{d_h - d_p}{12})\text{^}3]\text{^}\frac{1}{6}$ 2.35

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

$Q_{crit} = 0.04079(d_h^2 - d_p^2) * V_{min}$

2.5.4 ZEIDLER’S SLIP VELOCITY CORRELATION

Zeidler 1972 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 (Vs) of the drilled particles in a Newtonian fluid:

$2 \leq \mathrm{N_{RE,p}} \leq 15$

$V_S = 13.42 \frac{(\rho_s - \rho_l)^{0.782} * d_{eq}^{1.35}}{\rho_l^{0.218} * \mu^{0.564}}$ 2.36

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

$V_S = 13.88 \frac{(\rho_s - \rho_l)^{0.612} * d_{eq}^{0.836}}{\rho_l^{0.388} * \mu^{0.224}}$ 2.37

$80 \leq \mathrm{N_{RE,p}} \leq 1500$

$V_S = 17.88 \frac{(\rho_s - \rho_l)^{0.516} * d_{eq}^{0.548}}{\rho_l^{0.48} * \mu^{0.032}}$ 2.38

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.

2.6 DEFINITION OF MINIMUM VELOCITY AND SLIP VELOCITY

2.6.1 MINIMUM VELOCITY: This is the sum of slip velocity and cutting generation velocity. If gaseated fluid velocity is higher than the minimum velocity, cuttings are carried out of hole properly. High and low fluid velocities cause problems.

2.6.2 SLIP VELOCITY: This is the velocity of cutting that falls down due to gravitation. In order to effectively clean the hole, effect of mud flow upward direction and mud properties must be greater than cutting slip velocity. Otherwise, cutting will fall down and create cutting bed.

CHAPTER THREE

METHODOLOGY

This chapter focuses on the methods used in carrying out the study. In this chapter, information will be provided on how the data were collected, the sources of the data and method of data analysis.

Specifically, the chapter contains the research design chosen for this research work, the data collection method, the sampling procedures, the sources from which the data are collected, the instrument used in carrying out the research work and finally, the method of analysis and presentation.

3.1 THE RESEARCH DESIGN

The research design chosen for this research work is the descriptive approach. In this descriptive research, coherent inferences will be drawn from series of available data.

3.2 RESEARCH TYPE

In this regard, relevant data for this study will be obtained mainly from secondary sources. This includes published and unpublished works. Published works such as textbooks, conference proceedings, and magazines/bulletins found relevant to the subject under review.

3.3 SAMPLING PROCEDURES

For simplicity, convenience, and easy accessibility, the sample for this research project is drawn mainly from the internet, and published works such as textbooks, journals, monograph and conference proceedings.

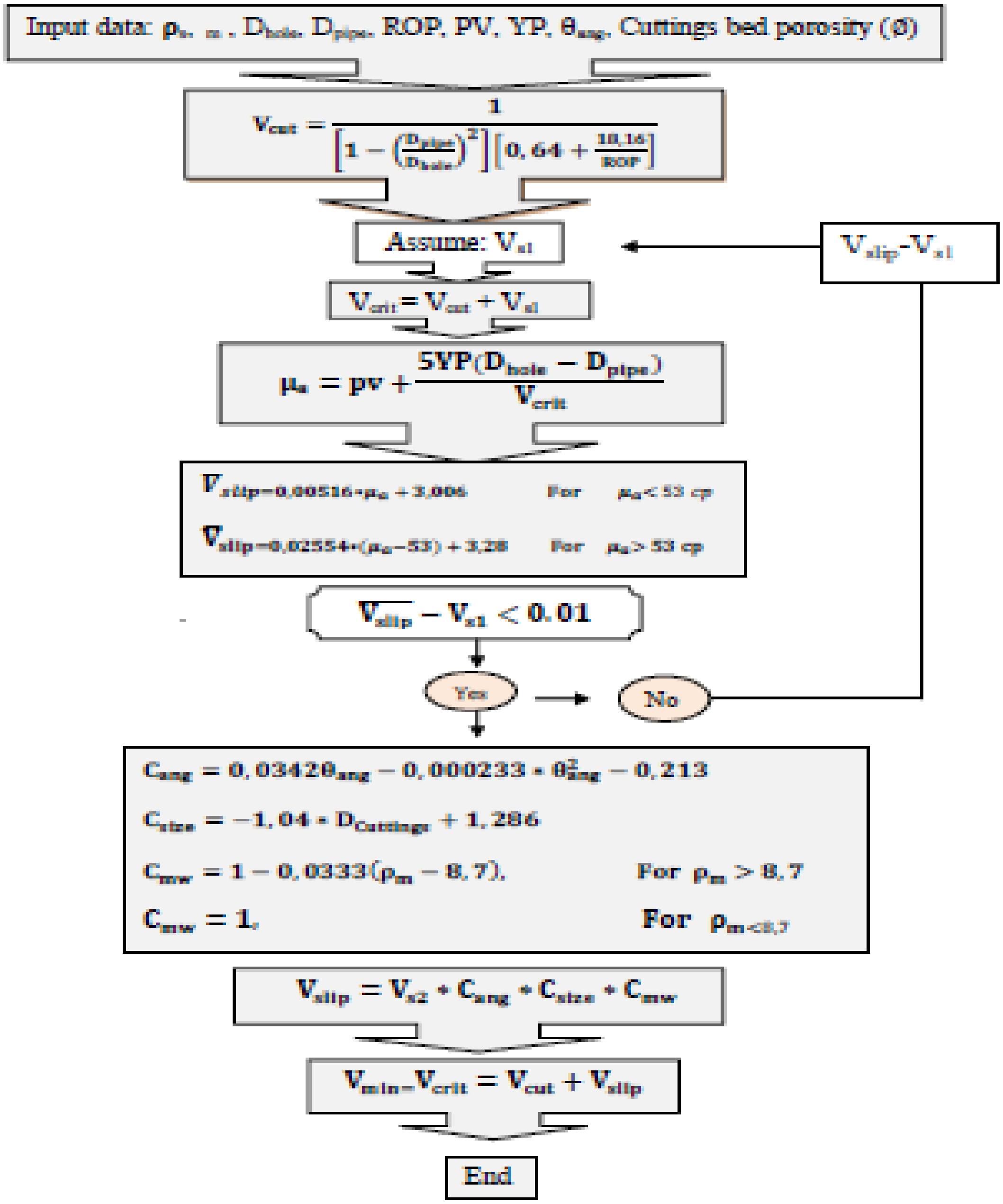
3.4 METHOD OF DATA ANALYSIS AND PRESENTATION

The data generated will be presented in a tabular form by the researcher and also with the aid of Microsoft Excel. The researcher intends to use a simple comparative analysis to represent the answers to the research questions. In this regard, the different formation configurations, different mud system, and potential damage that can happen during the course of using any of these mud systems will be taken into consideration in selecting the most effective and efficient drilling fluid for cutting transport mechanism.

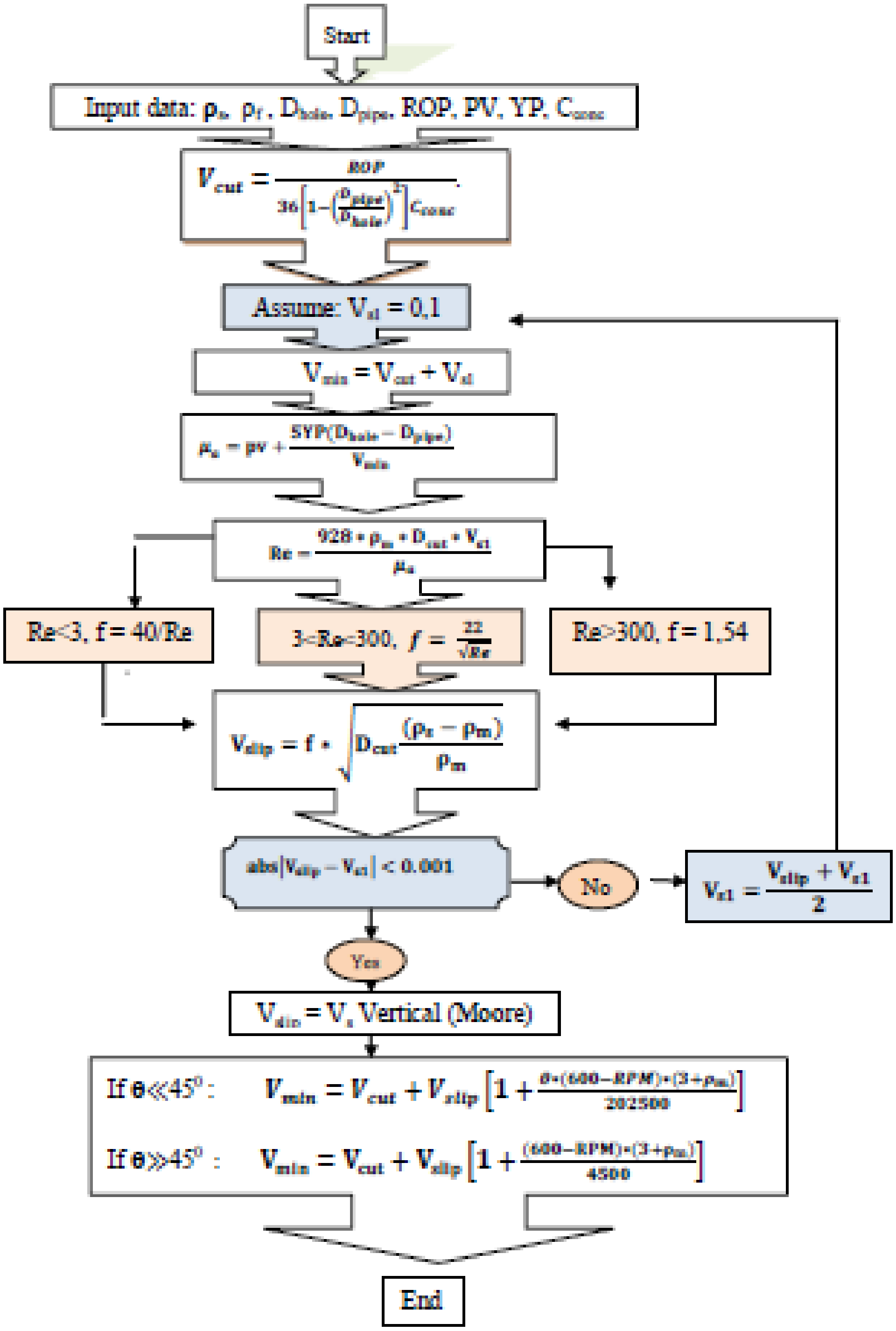
The data was further analyzed comparatively using Microsoft Excel. Microsoft Excel is a spreadsheet-based software tool that employs formulae and functions to arrange numbers and data. Excel analysis is used by businesses of all sizes all around the world to undertake various analysis. In this regard, the wellbore damage due to drilling will be quantified based on cutting transport parameters. The effects of these parameters on the different cutting transport models and the best model to be used in HTHP wells in niger delta.

3.5 SCHEMATIC FORM OF SOME OF THE MODELS

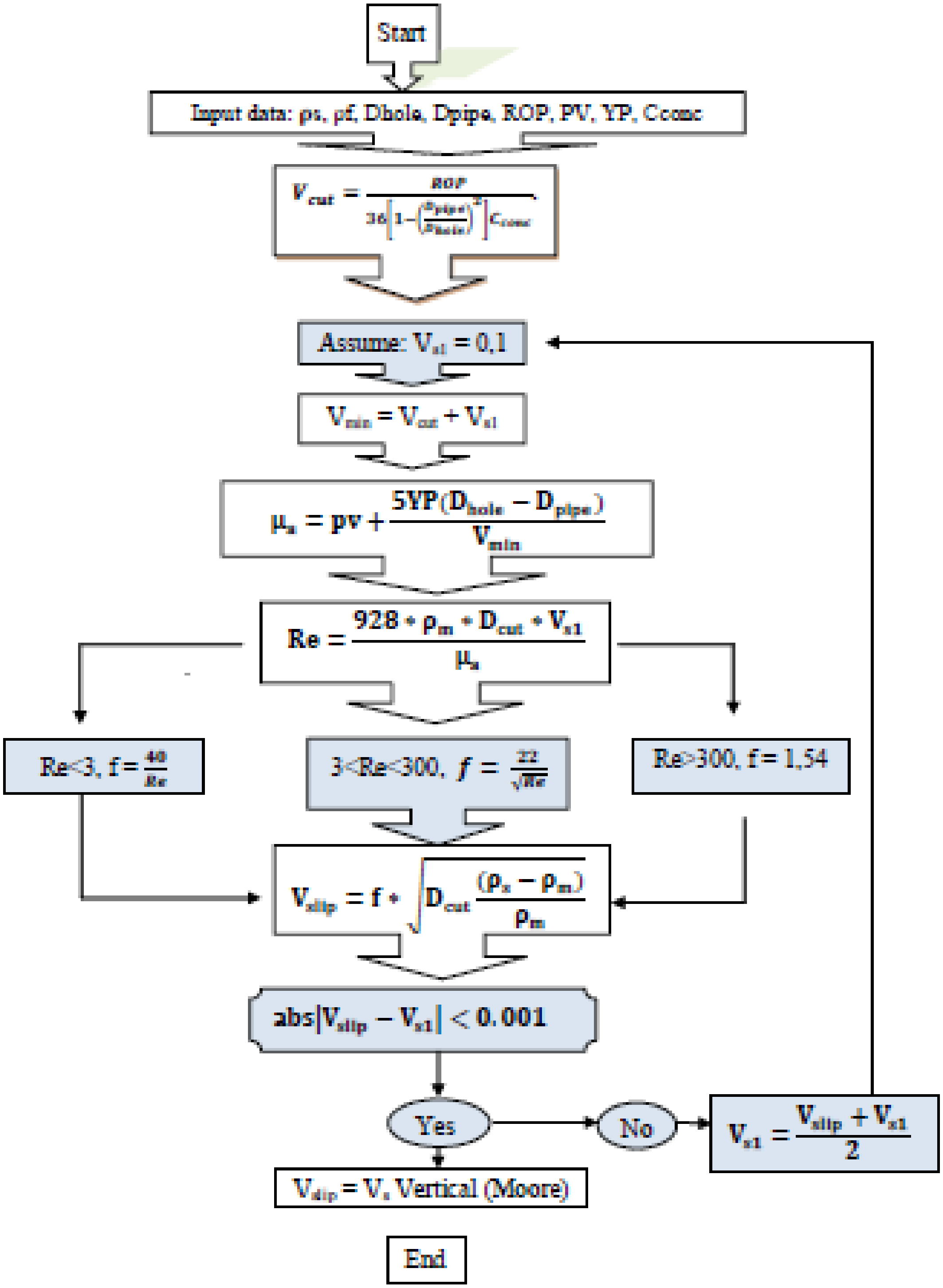
3.5.1 LARSEN’S MODEL IN SCHEMATIC FORM



3.5.2 Rudi Rubiandini's model in schematic form



3.5.3 Moore’s model in schematic form


Start
Input data: ρs, ρf, Dhole, Dpipe, ROP, PV, YP, Cconc
$V_{cut} = \frac{ROP}{36\left[1-\left(\frac{D_{pipe}}{D_{hole}}\right)^2\right]C_{conc}}$
Assume: $V_{s1} = 0{,}1$
$V_{min} = V_{cut} + V_{s1}$
$\mu_a = pv + \frac{5YP(D_{hole} - D_{pipe})}{V_{min}}$
$Re = \frac{928 * \rho_m * D_{cut} * V_{s1}}{\mu_a}$
Re<3, $f = \frac{40}{Re}$
3<Re<300, $f = \frac{22}{\sqrt{Re}}$
Re>300, f = 1,54
$V_{slip} = f * \sqrt{D_{cut}\frac{(\rho_s - \rho_m)}{\rho_m}}$
$abs|V_{slip} - V_{s1}| < 0.001$
Yes
No
$V_{s1} = \frac{V_{slip} + V_{s1}}{2}$
$V_{slip} = V_s$ Vertical (Moore)
End

3.5.3 MODIFIED LARSEN’S MODEL

The modified larsen’s model Follows same procedure as the larsens model except the addition of mud weight to apparent viscosity;

$$V_{cut} = \frac{1}{\left[1-(\frac{D_{pipe}}{D_{hole}})^\wedge 2\right][0.64+\frac{18.16}{ROP}]}$$

$$\mathrm{V}_{s1} = 0.45\left(\frac{PV}{MW * D_p}\right)[\sqrt{(\frac{36800 * D_P}{\left(\frac{PV}{MW * D_p}\right)^2} * \left(\frac{\rho_s}{MW} - 1\right) + 1\,)} - 1]$$

$$\mu_a = PV + \frac{5YP(D_{hole} - D_{pipe})}{V_{min}} + \rho_m$$

CHAPTER FOUR

RESULTS AND ANALYSIS

4.1 PARAMETERS FOR CUTTING TRANSPORT MECHANISM

4.1.1 CONSTANT PARAMETERS

Diameter of pipe (D_{pipe}) = 5(inches)

Diameter of hole (D_{hole}) = 8.5(inches)

Rate of penetration (ROP) = 33(ft/hr)

Plastic viscosity (PV) = 7(cp)

Yield point (YP) = 7(lbf/100ft^2

Diameter of cuttings/ cuttings size (D_{cut}) = 0.3(inches)

Mud weight (ρ_m) = 10.83 (ppg)

RPM = 80

Cuttings density (ρ_s) = 19(lbf/gal)

Inclinations = 0° to 90°

Empirical constant (C) = 40

Gravitational acceleration (g) = 9.81

4.1.2 Varying parameters

ROP(ft/hr)	33	98.3	164

Mud weight (ρ_m)	10.83	12.5	15
cuttings size (D_{cut})	0.1	0.3	0.6
Mud rheology(YP=PV)	7	10	15

4.2 MOORE’S MODEL ANALYSIS

For constant parameters

$$V_{cut} = \frac{1}{\left[1-(\frac{D_{pipe}}{D_{hole}})^{\wedge}2\right][0.64+\frac{18.16}{ROP}]}$$

$$\mathrm{V}_{cut} = \frac{1}{\left[1-(\frac{5}{8.5})^{\wedge}2\right][0.64+\frac{18.16}{33}]}$$

V_{cut} = 1.2846313

$\mathrm{V}_{\boldsymbol{cut}} \cong 1.28$

$$\mathrm{V}_{s1} = 0.45\left(\frac{PV}{MW * D_p}\right)[\sqrt{(\frac{36800 * D_P}{\left(\frac{PV}{MW * D_p}\right)^2}} * \left(\frac{\rho_s}{MW} - 1\right) + 1) - 1]$$

$$\mathrm{V}_{s1} = 0.45\left(\frac{7}{10.83 * 0.3}\right)[\sqrt{(\frac{36800 * 0.3}{\left(\frac{7}{10.83 * 0.3}\right)^2}} * \left(\frac{19}{10.83} - 1\right) + 1) - 1]$$

V_{s1} =40.1O899632ft/min

V_{s1} =0.6684832721ft/s

$\mathrm{V}_{min} = \mathrm{V}_{cut} + \mathrm{V}_{s1}$

V_{min} = 1.2846313 + 0.6684832721

V_{min} = 1.953114572ft/s

$$\mu_a = PV + \frac{5YP(D_{hole} - D_{pipe})}{V_{min}}$$

$$\mu_a = 7 + \frac{5(7)(8.5-5)}{1.953114572}$$

$\mu_a = 69.72033487$ cp

$$R_e = \frac{928 * \rho_m * D_{cut} * V_{s1}}{\mu_a}$$

$$R_e = \frac{928 * 10.83 * 0.3 * 0.6684832721}{69.72033487}$$

$R_e = 28.90871365$

Since, 3< $R_e < 300$

$\mathrm{F} = \frac{22}{\sqrt{R_e}} = \frac{22}{\sqrt{28.90871365}}$

F = 4.09174252

$$\mathrm{V}_{\mathrm{slip}} = \mathrm{f} * \sqrt{\frac{\mathrm{D}_{\mathrm{cut}} * (\rho_{\mathrm{s}} - \rho_{\mathrm{m}})}{\rho_{\mathrm{m}}}}$$

$$V_{\text{slip}} = 4.09 * \sqrt{\frac{0.3 * (19 - 10.83)}{10.83}}$$

$V_{\text{slip}} = 1.945721758 \text{ ft/s}$

$V_{\text{slip}} = V_{\text{s}}$ vertical (moore)

For varying parameters

First case

ROP(ft/hr) = 33

Mud weight(ppg) =10.83

Cuttings size(inch) =0.1

Mud rheology(PV=YP) =7

V_{cut} = 1.2846313

$$V_{s1} = 0.45\left(\frac{7}{10.83 * 0.1}\right)[\sqrt{(\frac{36800 * 0.1}{\left(\frac{7}{10.83 * 0.1}\right)^2} * \left(\frac{19}{10.83} - 1\right) + 1\ )} - 1]$$

V_{s1} =20.97924021ft/min

V_{s1} =0.3496540034ft/s

$V_{min} = V_{cut} + V_{s1}$

$V_{min} = 1.2846313 + 0.3496540034$

$V_{min} = 1.634285303$ft/s

$$\mu_a = 7 + \frac{5(7)(8.5-5)}{1.634285303}$$

$$\mu_a = 81.95631257cp$$

$$R_e = \frac{928 * 10.83 * 0.1 * 0.3496540034}{81.95631257}$$

$$R_e = 4.287780332$$

Since; $3 < R_e < 300$

$F = \frac{22}{\sqrt{4.287780332}} = 10.62444902$

$$V_{slip} = 10.62 * \sqrt{\frac{0.1 * (19 - 10.83)}{10.83}}$$

$V_{slip} = 2.916898497$ft/s

similarly case 2 and 3 was calculated for using same analysis above

CONSIDERING VARYING INDIVIDUAL PARAMETERS

For ROP, using 33ft/hr

$V_{cut} = 1.2846313$ft/s

$V_{s1} = 0.6684832721$ft/s

$V_{min} = 1.953114572$ft/s

μ_a = 69.72033487 cp

R_e = 28.90871365

F = 4.09174252

V_{slip} = 1.945721758 ft/s

Similar calculation was done for 98.3ft/hr and 164ft/hr.

For mud weight (ppg)

Using 10.83

V_{cut} = 1.2846313ft/s

V_{s1} =0.6684832721ft/s

V_{min} = 1.953114572ft/s

μ_a = 69.72033487 cp

R_e = 28.90871365

F = 4.09174252

V_{slip} = 1.945721758 ft/s

Similar calculations was done for 12.5 and 15

For cuttings size (inches)

Using 0.1

V_{cut} = 1.2846313ft/s

V_{s1} = 0.3496540035ft/sec

$V_{min} = 1.2846313$ +0.3496540035

V_{min} = 1.634285304ft/s

μ_a = 81.95631255cp

R_e = 4.287780334

F =$\frac{22}{\sqrt{4.287780334}}$

F= 10.62444902

$$V_{\text{slip}} = 10.62 * \sqrt{\frac{0.1 * (19 - 10.83)}{10.83}}$$

V_{slip} = 2.916898497ft/s

Similar calculations was done using 12.5 and 15

For mud rheology (PV=YP)

Using 7

V_{cut} = 1.2846313ft/s

V_{s1} =0.6684832721ft/s

V_{min} = 1.953114572ft/s

$\mu_a = 69.72033487$ cp

R_e = 28.90871365

F = 4.09174252

$\mathrm{V_{slip}}$ = 1.945721758 ft/s

Similar calculations was done using 10 and 15

4.3 RUDI-RUBIADINI'S MODEL

For constant parameters

Using data's from moore's model

$\mathrm{V_{slip}}$ = 1.945721758 ft/s

If $\boldsymbol{\theta \ll 45^0}$

$V_{min} = V_{cut} + V_{slip}\,[1 + \frac{\theta(600-RPM)*(3+\rho_m)}{202500}]$

$\boldsymbol{\theta \gg 45^0}$

$V_{min} = V_{cut} + V_{slip}\,[1 + \frac{(600-RPM)*(3+\rho_m)}{4500}]$

Considering $\boldsymbol{\theta \ll 45^0}$

$V_{min} = V_{cut} + V_{slip}\,[1 + \frac{\theta(600-RPM)*(3+\rho_m)}{202500}]$

At $\mathbf{30^0}$

V_{min} = 1.2846313 + 1.945721758$[1 + \frac{30(600-80)*(3+10.83)}{202500}]$

V_{min} = 5.303368257ft/s

At $\mathbf{15^0}$

V_{min} = $1.2846313 + 1.945721758[1 + \frac{15(600-80)*(3+10.83)}{202500}]$

V_{min} = 4.266860658ft/s

considering $\boldsymbol{\theta} \gg \mathbf{45^0}$

V_{min} = $1.2846313 + 1.945721758[1 + \frac{(600-RPM)*(3+10.83)}{4500}]$

V_{min} = $1.2846313 + 1.945721758[1 + \frac{(600-80)*(3+10.83)}{4500}]$

V_{min} = 6.339875857ft/s

For varying parameters

First case

ROP(ft/hr) = 33

Mud weight(ppg) =10.83

Cuttings size(inch) =0.1

Mud rheology(PV=YP) =7

V_{slip} =2.916898497ft/s

If $\boldsymbol{\theta \ll 45^0}$

For $\mathbf{30^0}$

$V_{min} = 7.309258276 ft/s$

For $\mathbf{30^0}$

$V_{min} = 5.7553594036 ft/s$

Second case

ROP(ft/hr) = 98.3, = $\rho_m(ppg) = 12.5$, $D_{cut} = 0.3$, YP=PV=10.

Similar calculations was done.

Third case

ROP = 164, $\rho_m(ppg) = 15$, $D_{cut} = 0.6$, YP=PV=15.

Similar calculations was made.

CONSIDERING VARYING INDIVIDUAL PARAMETERS

Similar calculations was made for all the varying parameters

4.4 LARSEN'S MODEL

For constant parameters

$\mu_a = 69.72033487$ cp

Since $\mu_a > 53\ cp$

∇_{slip} = 0.02554*($\mu_a - 53$)+3.28

∇_{slip} = 0.02554*($69.72033487 - 53$) + 3.28

∇_{slip} = 3.707037353ft/s

Considering different angles $\boldsymbol{\theta}$

Say, $\mathbf{30^0}, \mathbf{45^0}, \boldsymbol{and}\ \mathbf{60^0}$

C_{ang} =0.0342($\boldsymbol{\theta}$) -0.000233($\boldsymbol{\theta}$)^2 -0.213

For $\mathbf{30^0}$

C_{ang} =0.0342(30) -0.000233(30)^2 -0.213

C_{ang} = 0.6033

$C_{size}\ = 0.3$

$C_{mw}\ =$ 1 - 0.0333(ρ_m-8.7)

Since ρ_m > 8.7

ρ_m = 10.83

$C_{mw}\ =$ 1 - 0.0333(10.83-8.7)

$C_{mw}\ =$ 0.929071

$V_{slip} = \overline{V}_{slip} * C_{ang} * C_{size} * C_{mw}$

$V_{slip} = 3.707037353 * 0.6033 * 0.3 * 0.929071$

V_{slip} = 0.623347822ft/s

$V_{min} = V_{crit} = V_{cut} + V_{slip}$

$V_{min} = V_{crit} = 1.2846313 + 0.623347822$

$V_{min} = V_{crit} = 1.907979122 ft/s$

For $\mathbf{45^0}$

$C_{ang} = 0.0342(45) - 0.000233(45)^2 - 0.213$

C_{ang} = 0.854175

$C_{size} = 0.3$

$C_{mw} = 1 - 0.0333(\rho_m - 8.7)$

Since $\rho_m > 8.7$

$\rho_m = 10.83$

$C_{mw} = 1 - 0.0333(10.83 - 8.7)$

$C_{mw} = 0.929071$

$V_{slip} = \overline{V}_{slip} * C_{ang} * C_{size} * C_{mw}$

$V_{slip} = 3.707037353 * 0.854175 * 0.3$*0.929071

V_{slip} = 0.882559466ft/s

$V_{min} = V_{crit} = V_{cut} + V_{slip}$

$V_{min} = V_{crit} =$ 1.2846313+ 0.882559466

$V_{min} = V_{crit} = 2.167190766 ft/s$

For $\mathbf{60^0}$

C_{ang} =0.0342(60) -0.000233(60)^2 -0.213

C_{ang} = 1.0002

$C_{size} = 0.3$

C_{mw} = 1 - 0.0333(ρ_m-8.7)

Since ρ_m > 8.7

ρ_m = 10.83

C_{mw} = 1 - 0.0333(10.83-8.7)

C_{mw} = 0.929071

$V_{slip} = \bar{V}_{slip} * C_{ang} * C_{size}$ *C_{mw}

$V_{slip} = 3.707037353 * 1.0002 * 0.3 * 0.929071$

V_{slip} = 1.033436916ft/s

$V_{min} = V_{crit} = V_{cut} + V_{slip}$

$V_{min} = V_{crit} = 1.2846313 + 1.033436916$

$V_{min} = V_{crit} = 2.318068216 ft/s$

For varying parameters

Similarly, calculations was made on the varying parameters.

CONSIDERING VARYING INDIVIDUAL PARAMETERS

Similarly, calculations was made on the others individual varying parameters.

4.5 HOPKINS MODEL

For constant parameters

Step 1

V_{cut} = 1.2846313

$$V_{s1} = 0.45\left(\frac{PV}{MW * D_p}\right)[\sqrt{(\frac{36800 * D_P}{\left(\frac{PV}{MW * D_p}\right)^2}} * \left(\frac{\rho_s}{MW} - 1\right) + 1) - 1]$$

V_s =40.1O899632ft/min

V_s =0.6684832721ft/s

Step 2

$F_{mw} = 2.117 - 0.1648\rho_m + 0.003681\rho_m^2$

$F_{mw} = 2.117 - 0.1648(10.83) + 0.003681(10.83^2)$

$F_{mw} = 0.7639564409$

Step 3

$V_s = F_{mw} * V_{sv}$

$V_{sv} = \frac{V_s}{F_{mw}} = \frac{0.6684832721}{0.7639564409}$

$V_{sv} =$ 0.8750279942ft/s

Step 4

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

Where,

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

$V_2 = 40*[(\frac{19-10.83}{10.83})*98.1^3*(\frac{8.5-5}{12})\wedge 3]\wedge\frac{1}{6}$

V_2 = 1.075933865ft/s

Considering varying individual parameter

SIMILAR CALCULATIONS ARE MADE FOR THE VARYING PARAMETERS.

4.6 ZEIDLER’S SLIP VELOCITY CORRELATION MODEL

For constant parameters

$V_{cut} =$ 1.2846313ft/s

$V_{s1} =$ 0.6684832721ft/s

$V_{min} =$ 1.953114572ft/s

$$\mu_a = PV + \frac{5YP(D_{hole} - D_{pipe})}{V_{min}}$$

$$\mu_a = 7 + \frac{5(7)(8.5 - 5)}{1.953114572}$$

$$\mu_a = 69.72033487cp$$

$$N_{RE} = \frac{928 * \rho_m * D_{cut} * V_{s1}}{\mu_a}$$

$$N_{RE} = 28.90871365$$

IF,

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

$$V_S = 13.42\frac{(\rho_s - \rho_l)^{0.782} * d_{eq}^{1.35}}{\rho_l^{0.218} * \mu^{0.564}}$$

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

$$V_S = 13.88\frac{(\rho_s - \rho_l)^{0.612} * d_{eq}^{0.836}}{\rho_l^{0.388} * \mu^{0.224}}$$

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

$$V_S = 17.88\frac{(\rho_s - \rho_l)^{0.516} * d_{eq}^{0.548}}{\rho_l^{0.48} * \mu^{0.032}}$$

Since, $N_{RE} = 28.90871365$

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

$V_S = 13.88\frac{(19-10.83)^{0.612}*0.3^{0.836}}{10.83^{0.388}*69.72033487^{0.224}}$

V_{slip} =2.813159004ft/s

4.7 MODIFIED LARSEN'S MODEL

$$V_{cut} = \frac{1}{\left[1-(\frac{D_{pipe}}{D_{hole}})^{\wedge}2\right][0.64+\frac{18.16}{ROP}]}$$

$$\mathrm{V}_{s1} = 0.45\left(\frac{PV}{MW * D_p}\right)\left[\sqrt{\left(\frac{36800 * D_P}{\left(\frac{PV}{MW * D_p}\right)^2} * \left(\frac{\rho_s}{MW} - 1\right) + 1\right)} - 1\right]$$

$$\mu_a = PV + \frac{5YP(D_{hole}-D_{pipe})}{V_{min}} + \rho_m$$

Tables for analysis

	Modified larsens model	Hopkins	larsens	Rudi	zeilders
angles	v_{min}	v_{min}	v_{min}	v_{min}	v_{min}
30	1.9544	1.1169	1.9080	5.6473	-
45	2.2330	1.2624	2.2624	< 45 / >45	-
60	2.3952	1.4276	2.3181	6.7725	-

Table 2 : values of minimum velocity and angles

ROP AS A VARYING PARAMETER

angles					
30	1.9545	1.1169	1.9080	4.2669	-
45	2.2330	1.2624	2.1672	< 45 / > 45	-
60	2.3951	1.4276	2.3181	6.3340	-

Table 3 : Rate of penetration values

MUD WEIGHT AS VARYING PARAMETER

angles					
30	1.9461	1.1169	1.8996	4.2669	-
45	2.2211	1.2624	2.1553	< 45 / > 45	-
60	2.3812	1.4276	2.3041	6.3399	-

Table 4: mud weight values

CUTTING SIZE AS VARYING PARAMETER

angles					
30	1.5226	0.8408	1.5071	7.3093	-
45	1.5237	1.008	1.5071	< 45/ >45	-
60	1.6792	1.1066	1.6535	6.3399	-

Table 5: cutting size values

MUD RHEOLOGY AS A VARYING PARAMETER

angles					
30	1.9379	1.1169	1.8910	5.3034	-

45	2.2090	1.2624	2.1431	< 45 / > 45	-
60	2.3670	1.4276	2.2899	6.3399	-

Table 6: mud rheology values

SLIP VELOCITY

angles					
30	0.6699	0.6684	0.6233	1.9457	-
45	0.9484	0.6684	0.8826	1.9457	-
60	1.1105	0.6684	1.0334	1.9457	-

Table 7: slip velocity

4.8 GRAPHICAL REPRESENTATION

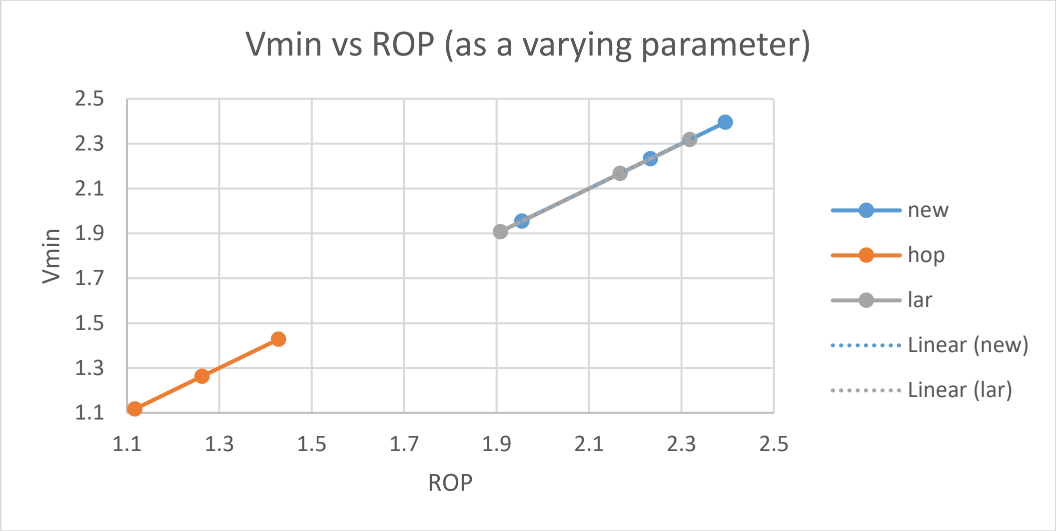


Figure 4. 1 A graph of Vmin vs ROP

this figure demonstrates that higher ROP requires higher flow velocity for effective cutting transport.from the graph the new modified larsens equation gives a higher minimum velocity to lift cuttings compared to the Hopkins and larsens model.

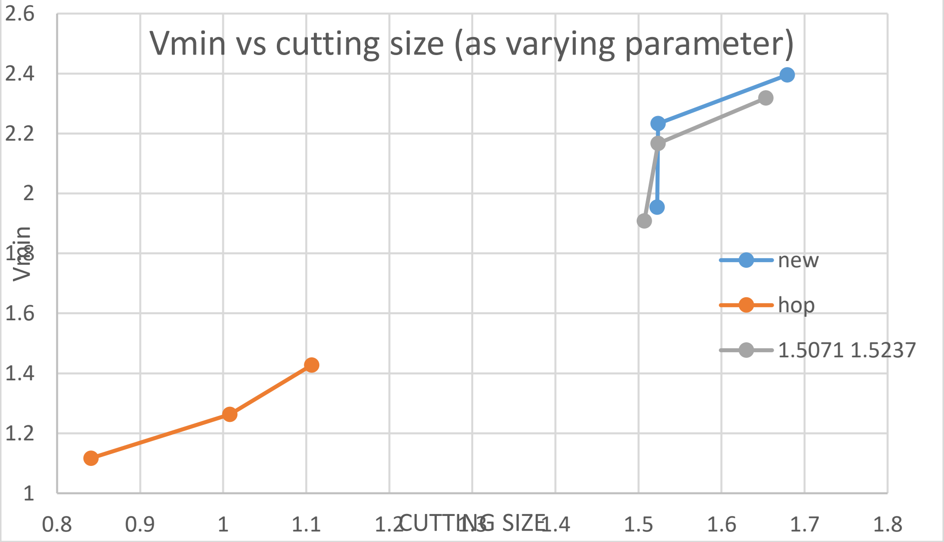


Figure 4. 2 A graph of Vmin vs cutting size

The graph demonstrates that bigger cuttings are more difficult to transport since they require higher flow rate than smaller cuttings.

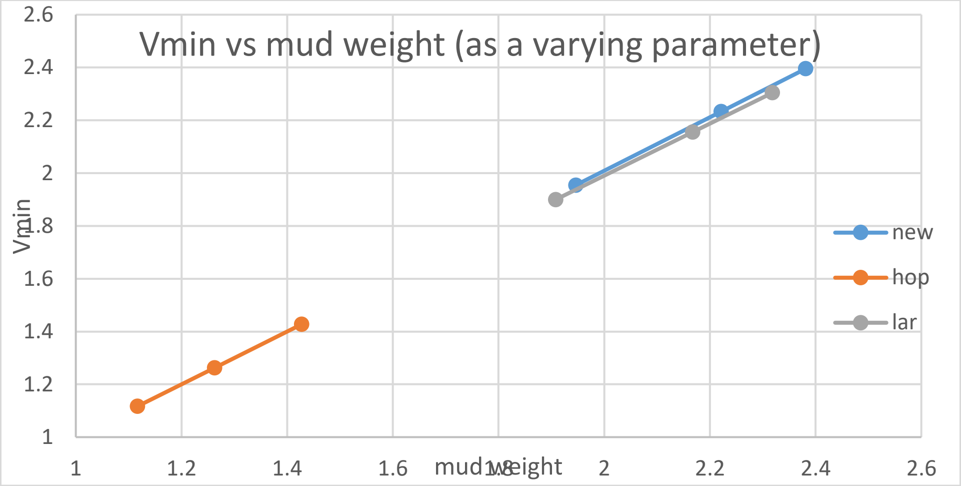


Figure 4. 3 A graph of Vmin vs mud weight

The higher the mud weight the higher the minimum velocity to lift the cuttings and is good for improving cutting transport.

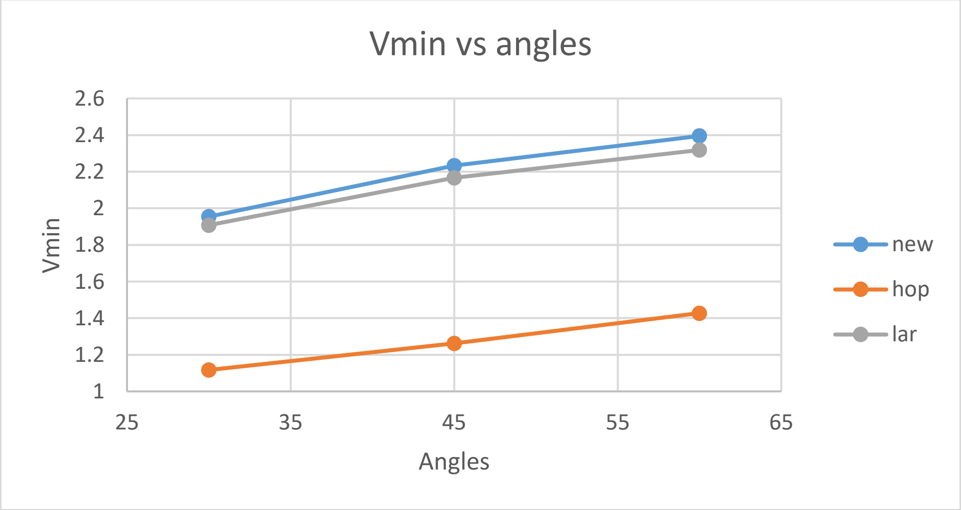


Figure 4. 4 A graph of Vmin vs angles

The higher the angles the more difficult to lift the cuttings during drilling and higher the velocity it will requires.

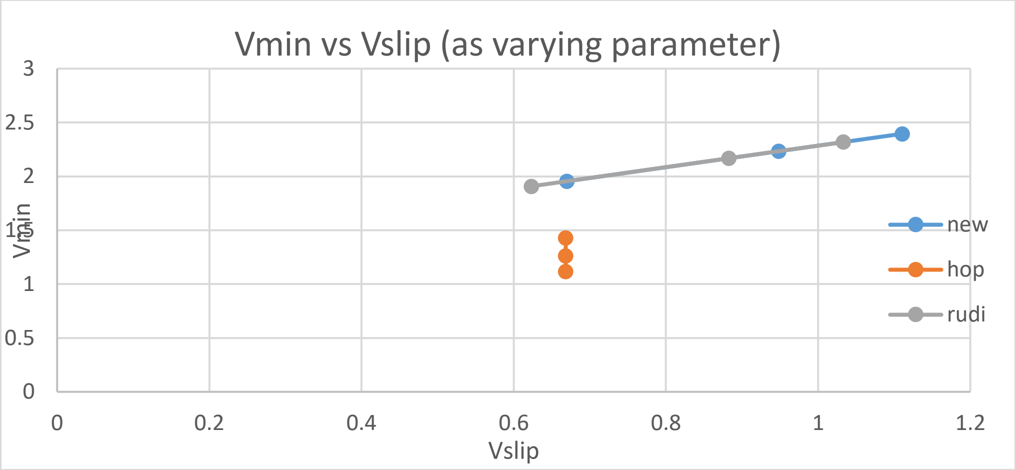


Figure 4. 5 A graph of Vmin vs Vslip

The higher the slip velocity, the more it is difficult to lift cuttings and requires higher velocity for transport.

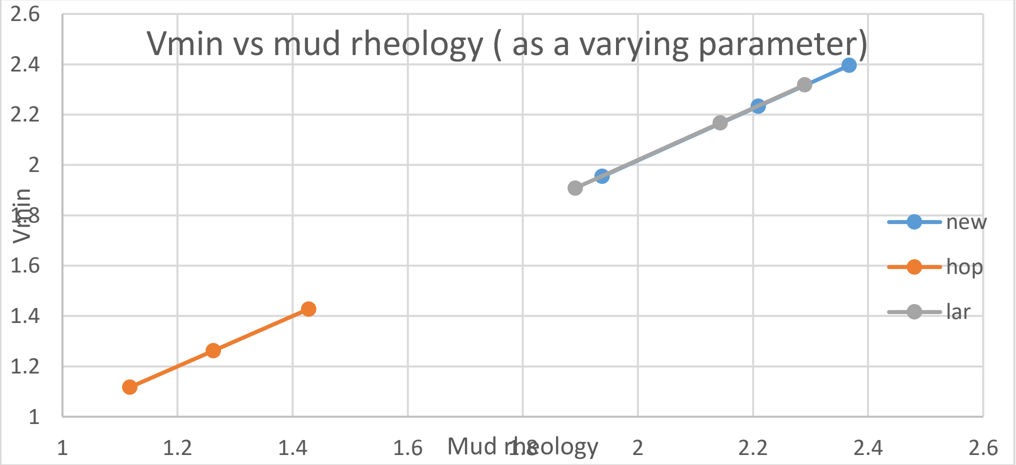


Figure 4. 6 A graph of Vmin vs mud rheology

Large mud rheology parameters lead to an increase in required flow rate for cuttings transport. All the models show this tendency, the new modified larsens model gives a higher and better minimum velocity.

4.9 DISCUSSION

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. for any well inclination and under all operational conditions the higher the flow rate clean the well effectively.

4.9.1 EFFECTS OF SOME MAJOR DRILLING PARAMETERS ON CUTTINGS TRANSPORT

MUD RHEOLOGY: Moderate positive or negative effect depending on cuttings size, pipe rotation, hole inclination and annular eccentricity. Mud rheology has moderate effect on small cuttings removal compared to large cuttings.

MUD WEIGHT: Small positive impact. A small increase in mud density decreases the cuttings bed height, increase in mud density with the same rheology has very small or no effect on hole cleaning.

RATE OF PENETRATION (ROP): Moderate negative impact. Increase in ROP increase hydraulic requirement for effective hole cleaning.

CUTTING SIZE: Small negative or positive impact depending on several conditions, smaller cuttings are more difficult to remove.

For all the models analyzed, flow velocity decreases as mud weight increases.

4.9.2 ADVANTAGES AND DISADVANTAGES OF THE MODELS

The advantage of using Larsen’s model and the modified Larsen’s model is the ability to predict the transport flow velocity that is required for cuttings transport at different inclination angles. Especially, this method is advantageous when it shows a higher flow velocity in the interval between 65° and 75° degrees. Larsen developed correction factors for angle of inclination, cuttings size, and mud weight. However, the Larsen‟s model is not applicable for the vertical wellbore, since the model was designed for high angle holes from 55° to 90° degrees.

By using Rubiandini‟s model, it is possible to calculate the minimum flow velocity for both vertical and horizontal wellbore since the model was developed for inclination angles 0° to 90° degrees. The main advantage of Rubiandini‟s model compared to Larsen‟s model is that Rubiandini, in his research took RPM in to consideration.

The modeling in this thesis revealed that Rubiandini’s model is not sensitive for small-sized cuttings. In addition, predictions from Rubiandini’s model contradict observations from Larsen’s model, namely that larger cuttings are more difficult to transport. The modeling in this thesis revealed that larger drill pipe required larger flow velocity for cuttings transport.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

CONCLUSION

The result of the analysis conducted on all the models shows that the larsens model gives a higher value of minimum velocity at different angle sections of the hole which is given by, 1.9080, 2.2624, and 2.3181 at 30, 40 and 60 degrees respectively compare to the other models which gives 1.1169, 1.2624 and 1.4276 for Hopkins, while rudi considers only angles >45 and < 45.

The improved model which is the modified larsens model gives a higher minimum velocity of 1.9544, 2.2330 and 2.3952 at 30, 40 amd 60 degrees, hence the improved model clean the hole and lifts the cuttings more effectively to the surface compare to other models analysed.

RECOMMENDATIONS

The following suggestions are recommended to achieve better hole cleaning and cuttings transport:

It is important to monitor the shakers before trip out (or pull out) in order to ensure that cuttings return rate has reduced.

During drilling, if transport of cuttings is a problem, the flow rate should be increased to its upper level, especially in the range of higher angles between 55° to 90° degrees. One has to be aware that inclinations between 40° to 45° degrees are critical since cuttings can slide down during e.g. connections when pumps are off.

Small cuttings create more packed cuttings bed. The height of cuttings bed is higher at inclination between 65° to 70° degrees, since hole cleaning is more difficult in this interval. In this case, a high rotary speed with a high viscosity mud would benefit to transport small-sized cuttings. When the drill pipe does not rotate, a low viscosity mud cleans the wellbore better than high viscosity mud.

FUTURE WORK

One can in the future design a model 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.

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