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Author:

Sindre B. Gåseland

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(signature author)

Course coordinator:

Arild Saasen

Supervisor(s):

Arild Saasen

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Abstract

This paper is looking on recent developments in hole cleaning technologies and how recent advancements can be used to aid efficient hole cleaning in deviated wells. Successful hole cleaning relies upon integrating optimum drilling fluid properties with the best drilling practices. The ability of the drilling fluid to transport the drilling cuttings to the are determined by several parameters (cutting density, mud weight, hole-size, hole-angle, rheology of fluid, cutting size, rate of penetration, drill pipe eccentricity, drill pipe rotation speed, phase of fluid, cutting transport ratio and cutting bed properties).

Efficient hole cleaning of deviated wells is important and difficult to perform efficiently, deviated wells normally uses drilling fluid with lower viscosity and gel building properties than in vertical section. Deviated wells are an important tool to either boost the return from existing fields or gaining access to new and formerly inaccessible formations. The increasing need for oil and gas have kept increasing with ever increasing energy output in the world, despite the world trying to swap to more renewable resources. Petroleum products such as coal, gas and oil still stand for over 80% of the energy production in the world. Increasing energy demands from the world exceeds the development within renewable technologies and gaining access to new formation and extracting most of the oil and gas in current formation will be paramount in giving people access to energy required to keep the world running. Percentage of world’s energy coming from renewable resources has increased and will hopefully keep increasing, but total energy demand especially from developing countries with increasing population and higher standard of living requires higher amount of energy than the countries are currently consuming with renewable being too expensive, inefficient, or lacking the required infrastructure for implementation. The paper is a compilation of recent developments and would hopefully give the reader insight in the processes most important efficient hole cleaning for deviated wells.

The topic of efficient hole cleaning is complex, and a lot of different parameters will be introduced to understand the role of new developments. Basic understanding of these parameters and their interplay with each other is required to understand to keep the innovation with respect to efficient hole cleaning and automating more of the process involved in hole cleaning while drilling in deviated wells.

The paper also uses the information from collected studies to write to a data code based on recent developments to aid in controlling the right rate of penetration (ROP) during drilling. No independent research was those in this paper and is based on the work of research and literature of others.

Acknowledgements

Reading studies and papers written by authors with much more knowledge than me and being able to just build on the work from others and relay their results feels like the saying from Isaac Newton

“If I have seen further than others, it is because I’ve stood on the shoulders of giants”

Not because this article brought anything innovative or new, but because work done by those who came before us is benefitting us today and experiments from different parts of the world keep pushing us towards a better understanding. The innovation within computer technology and the ability to share and process information has been giant leaps forward. Information and knowledge that were formerly not be publicly available to most people are today easily available today through the internet. Equation 10 discussed in this paper and used in the coding example was found by Tobenna at University of Stavanger in 2010 giving us a mathematical formula able to describe CCI for deviated wells. I am thankful for his impact on this paper through his work. Myself being a student at the University of Stavanger I found it inspiring to be able to use work from former students.

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Introduction

Effective hole cleaning is heavily dependent on several parameters. 5 of the most important parameters and things we as engineers should take into consideration:

- Well design (hole angle, drill pipe eccentricity, well trajectory)
- Drilling fluid properties (PV, YP, YP/PV-ratio, gel strength, mud weight)
- Properties of drilled formation (Lithology, cuttings S.G, size, and shape)
- Hydraulic optimization (flow regime, nozzle size selection, number of nozzles)
- Drilling practices (Drill pipe rotation speed, wellbore tortuosity, bit type, rate of penetration (ROP) and pump rate)

Traditional wells are drilled straight down and are called vertical wells. Wells deviating from vertical paths are referred to as deviated wells. Drilling deviated wells requires special tools and configurations such as whipstocks, changes to the bottomhole assembly and equipment to give feedback on the 3-D direction. Changing the direction of the drilling causes a lot of stress on the equipment, specifically increased torque. The increase in torque demands changes in other parameters of the drilling, such as the properties of the drilling fluid. Essential properties for most drilling fluids are removal of cuttings, suspend cutting and weight material during stop in drilling or circulation, transporting cuttings to surface, add buoyancy to the drill string, cool and lubricate the bit and drill string, maintaining filter cake to avoid loss of fluid to formation and control the pressure in the well. During directional drilling the property of mud to lubricate and cool down the drill pipe are essential, and the drilling fluids with the ability to reduce friction become more important. The rheology of the drilling fluid is often a trade-off, where the mud engineer is responsible for designing a fluid with the desired properties. Increasing the viscosity of the fluid, will lead to more friction and more energy output by the top drive to keep the drill rotation speed constant. This explains some of the difficulties occurring during directional drilling, and why hole cleaning is more difficult in these wells. The risk of stuck pipe is much greater during directional drilling, where friction forces could make drill unable to rotate. Drilling fluids used in vertical wells often have strong thixotropic properties, a property which makes the drilling fluid able to float and keep weighting material and cuttings afloat should the drilling and circulation of fluid stop. This property is a time dependent property which makes it more gel-like with over time and less viscous when it is kept in motion, like during drilling. Drilling fluid with strong gel building properties in directional drilling, where torque and friction are already adding strong inhibitory forces to drill string rotation combined with a gel building drilling fluid would greatly increase the risk of stuck pipe during extended period of stop in the drilling. Up until the 1990s where the technology and use directional drilling where uncommon drilling fluids were mainly used for and specified for vertical wells.

1. Oil-based muds vs water-based muds

Oil-based muds (OBM) has a lot of the required properties for directional drilling. Oil works well as a lubricating fluid, enhancing the drilling efficiency with little maintenance and almost does not interact with the surrounding formations. The continuous phase in OBM is different kind of oils, usually diesel, while WBM has a continuous phase of water. Both fresh water and salt water can be used and are often chosen according to what will work best for each formation. Water based muds (WBM) interacts more with surrounding formation, and in troublesome areas such as troublesome shale, salt, or HPHT-conditions the usage of WBMs could be troublesome. OBM are more resistant to changes in temperature, interacting and normally migrating less to surrounding formation. Loss of OBM to surroundings are generally considered to be between 0,5-1.5, while WBM losses are estimated between 2-6 depending on conditions in the formations. Mineral OBM are toxic to the environment, and are not easily biodegradable, thus having negative environmental effects. Ongoing research into more biodegradable and economic viable solution is being done, and several companies has been testing different vegetable oils. They are unfortunately more expensive, due to an already existing market, and several companies are looking for different alternatives than the vegetable oils currently used for human consumption (Agwu, OE et al. 2015).

Hole cleaning is more difficult with OBM. The cuttings will not disband into the OBM as with WBM. OBM is more Newtonian than WBM and OBM therefore has less thixotropic properties than WBM. More often leading to poor hole cleaning performance and cuttings accumulation in the annulus of the well. WBM are usually cheaper and more environmentally friendly and consist of either saltwater or freshwater with the addition of different polymers to gain the required properties. Due to water interacting and migrating more than OBM for WBM we should consider the osmotic pressure of the fluid and should ideally be kept equal to surrounding formation. This reduces water migrating to or from the fluid from the surrounding formation water.

2. Common additives

Additives usually constitute 3-4% and the pH of the water is usually around 8,5-9,5, due to polymers added to the water being more efficient around this temperature ensuring good filter cake and minimizing loss of water to formation. Most used weighting material is baryte, with a specific gravity around 4,2. Baryte is used in both OBM and WBM. Other alternatives are ilmenite, Micromax and hematite. Bentonite is used in both muds as viscofier and gelling agent, but to work in OBM bentonite must be chemically treated with an amine group to efficiently interact in the oil. Polymer additives most used in drilling fluids are xanthan gum, starch, carboxymethyl cellulose, hydroxypropyl starch, lignin, and lignosulfonate. The polymers are often temperature dependent and will deteriorate under high temperatures. Oil based muds can be formulated to withstand high temperatures over long periods of time, while OBM under these conditions typically break down and lose its properties like loss of viscosity or ability to maintain a good filter cake. Historically OBM has therefore been used in HPHT-wells. More countries in the world have put into place environmental regulations that prohibit the discharge of oil-based muds and its cuttings. Higher cost of OBM, combined with its environmental impact has created a market for WBM, which could withstand HPHT-conditions. Temperature above 150° or pressure above 69MPa (rated working pressure) are generally considered HPHT.

3. Circulation system

Circulation system responsible for lifting and removing the cutting and maintaining the quality of drilling muds. Principal components of the rig circulating system include mud mixing equipment, mud pits, mud pumps and contaminant removal equipment. Drilling mud most important qualities are balancing the pore pressure, transporting cuttings, keeping it afloat during circulation stop, stabilizing borehole, create a filter cake to avoid loss of fluid, cool and lubricate drill pipe and string and protect the formation. Choosing a fluid or mixing mistakes can be detrimental for well. Information about the formation being drilled are therefore beneficial, such as pressure in well, salinity of formation fluid, cave ins or unstable sections. The drilling fluid can be used to protect the drilling equipment from corrosion and the effects of wear and tear. Oil-based muds could also have health risks for the personnel responsible for handling and mixing of the equipment. New development of more efficient shakers who wear down more slowly has reduced the time and personnel required to operate an efficient circulating system. Common WBMs are inexpensive but maintaining the right properties while drilling and remove the contaminants returning from the well increases the cost. The person generally in charge of this process is called the drilling fluid engineer and is responsible for keeping the mud in good condition at the lowest possible cost. The most used drilling fluid is liquid either oil or water, but there exist more alternatives should the formation have special requirements. In addition to liquid there is gas-liquid mixtures or just pure gas fluids. Gas-liquid mixtures can be used when only a few formations capable of producing water at significant rates are encountered and has been shown to give higher ROP in extreme conditions like permafrost (Sadirovich, 2020). Use of gas as a drilling fluid requires that the formation being drilled is competent and impermeable.

4. Rheology

4.1 Newtonian vs non-newtonian fluids

Rheological properties of the drilling fluid play an important role in the cleaning process of wells. The need to provide the cuttings with lift required to transport the cuttings to the surface. Rheology tries to explain the behavior of fluids under different conditions such as temperature, pressure and external forces. It studies how drilling muds deforms and flows under these different conditions with regards to the fluid's elasticity, plasticity, and viscosity. There are four commonly used rheological models used to describe the behavior of fluid and how it changes when it exposed to shear forces. The fluid could act as a Newtonian fluid if its viscosity only varies in response to changes in temperature or pressure. Non-Newtonian fluids has properties of liquid and of a solid. It can flow like a fluid while under different conditions have elasticity, plasticity, and strength like a solid. For drilling purposes, we focus mostly on thixotropic and pseudoplastic fluids. Pseudoplastic fluids decreases its viscosity with increasing shear rate. Thixotropic fluids more illiquid/solid after we stop stirring. Good muds in vertical wells often exhibit both thixotropic and pseudoplastic characteristics. High viscosity under low shear forces and good thixotropic effects adds to much friction to the drill pipe increases the chances of stuck pipe or excessive ECD. Flow behavior index is a useful tool in determining if we deal with a Newtonian or non-Newtonian fluid.

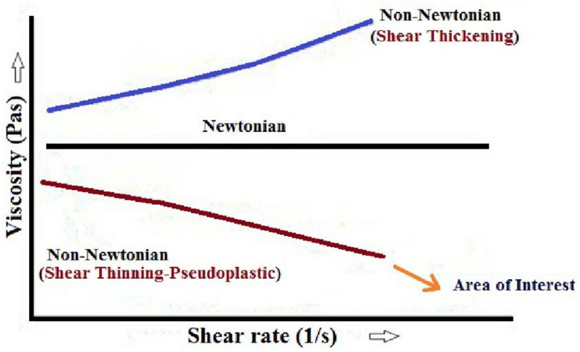

Figure 1 Behavior of different fluids when shear forces are applied, Baek,W 2013)

$$n = \frac{\frac{\log \tau_1}{\log \tau_2}}{\frac{\log y_1}{\log y_2}} \quad Eq. 1$$

- n > 1, dilatant fluid, non-Newtonian, shear thickening
- n = 1, Newtonian fluid
- n < 1, pseudoplastic, non-Newtonian, shear thinning

4.2 Rheological models

Most common rheological models used in drilling to describe fluids properties are either the Power law model, Bingham plastic or Herschel-Buckley model all three describing the behaviour of pseudoplastic fluids.

Bingham plastic model is where the plastic viscosity (PV) is the slope of the line and the starting point on the graph is referred to as yield point (YP). Yield point must be high enough to provide the cuttings with enough lift to be carried out of the well. Power law describes the behaviour more accurate than the Bingham-model from just two data points, but do not contain a yield point and underestimate the viscosity for low shear rates. Herschel-Buckley model is more accurate in describing the rheological behaviour when sufficient data are available and more accurate than the Bingham mode for low shear rates.

4.3 Viscosity

Viscosity is defined as the resistance of a substance to flow. Commonly differentiation or sub-sections of viscosity are funnel viscosity, apparent viscosity, plastic viscosity, yield point, low shear rate viscosity and gel strength. Funnel viscosity is often measured using the March-funnel and is used as a relative indicator of drilling fluid condition but does not give accurate information about the flow characteristics. It therefore just used as a control parameter for drilling muds. No explain changes in the mud we would have to look at the other parameters. Apparent viscosity is reported in oil field as the reading at 300RPM or half of the reading at 600 RPM with a viscometer. Plastic viscosity (PV) describes the resistance to flow caused by the mechanical friction. Causes for this friction could be due to solids concentration, size or shape of the solids, viscosity of the fluid phase and the oil-water ratio in invert emulsion drilling fluids. Solids are added to the drilling fluids to adjust fluids properties such as bentonite for viscosity and barite for density. Drilled solid or cutting are additional particles which can affect the planned properties. Excessive accumulation of solids in the mud can be removed by mechanically, settling, dilution or displacement. Increases in plastic viscosity can be related to increase in solids concentration, reduction of the solids size, a change in shape of solids or a combination of the above.

4.4 Plastic viscosity

The friction can be due to friction between the particles in the mud, between the particles and the fluid phase or between different fluids within the mud. Viscosity is also related to the fluid phase. In water viscosity decreases with the increase in temperature. It is calculated by reading of the value for the mud at 600RPM minus the value for mud at 300RPM.

$$PV = \theta_{600} - \theta_{300} \quad Eq. 2$$

4.5 Yield point

Yield Point occurs due to electro-chemical interactions within the drilling fluids. Molecules or particles with charged surfaces attract each other and can therefore be lowered with chemical treatments that reduces the charged surfaces, such as lignosulfonate or lignite. Chemical treatments that increase the charged surfaces could therefore be used to increase the viscosity and are called viscofiers, such as PAC (polyanioc cellulose) or CMC (carboxy-methylcellulose).

$$YP = 2 * \theta_{300} - \theta_{600} \quad Eq. 3$$

4.6 Shear rate

Low shear rate viscosity readings at 3 RPM and 6 RPM are trough laboratory studies and field experiments shown to be a better indicator for hole cleaning than yield point in highly deviated, horizontal, and extended reach wells. Under flowing conditions in deviated or horizontal wells low shear rate viscosity correlates to modified fluid properties, which enhances the transport of cuttings and avoids the accumulation of cutting deeper in the well. In static conditions the optimal low shear rate rheology should aid the suspension of particles, minimize the radial slip of cuttings, and decrease the likelihood for accumulation of cuttings beds.

4.7 Gel Strength

Gel strength is the fluid’s ability to form gel in static conditions and start to flow again when shear is resumed. Gel strength is associated with the attractive forces within the fluid. It is therefore dependent on number of solids in suspension, time, temperature, and chemical treatment. Excessive gel strength and strong gel building properties is not desired in deviated wells despite it being important in keeping solids in suspension. It is measured after running the viscometer on 600RPM, 15 seconds pause and make the reading at 3 RPM.

5. Settling of solids

Equation 10.1: Stoke's Law for settling solids (Stokes 1851)

$$V = \frac{g\left(\rho_1/\rho - 1\right)d^2}{18\upsilon}$$

where:
V = settling velocity of the solid
g = acceleration of gravity
ρ_1 = mass density of the solid
ρ = mass density of the fluid
d = diameter of the solid (assuming spherical)
υ = kinematic viscosity of the fluid

Figure 2 Stoke's law, http://stormwaterbook.safl.umn.edu/sedimentation-practices

Sedimentation occurs when forces of gravity and friction overcomes the force provided to cuttings by the fluid. Calculating the speed of sedimentation can be deduced from Stoke's law for settling solids shown in figure 2. The geometry of the solids is assumed to be spherical. Few cutting particles are perfectly spherical and settling speed vary from calculated value. Size is considered a parameter with less importance in efficiency of hole cleaning. Even though the size and density of the cuttings are the determining factors for the settling speed of the solids. The diameter being squared in the equation means that increase in diameter to twice the size gives 4 times as high settling speed. Forces acting in inclined wells can be divided into two groups, depositional or transport forces. The depositional forces consisting of gravitational and friction force. Gravitational force makes the cuttings settle down and form a bed. Frictional force is a force that acts against the cuttings movement sliding on the surface of the wellbore. Transport forces can be separated into lift and drag forces. Lift forces arising from the from the fluid velocity around the cuttings or by turbulent flow. The drag force rolls the cuttings out of the bed to move them forward (Roozbeh, R 2010).

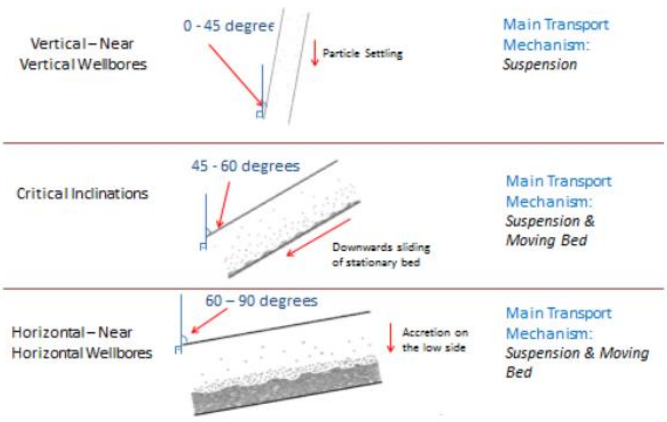

Figure 3 Transport of cuttings for different inclinations (Tomren et al 1986)

It is essential that the drilling fluid provides a drag force (F_D) higher than the force of gravity (F_g) on the cuttings. Higher force of gravity than drag force from the fluid lead to drop out of larger cuttings, leading to settling of cuttings. Meaning the drilling fluid is not able to carry the cuttings to surface and leading to accumulation of larger pieces of cuttings deep in well. The fluid should not have too high viscosity nor strong gel building characteristics in deviated wells. Drill rotation speed plays an important role in hole cleaning and would be negatively affected by high viscosity and would increase the risk of stuck in pipe if combined with high gel building characteristics if drilling must be stopped. High fluid velocities are often needed for efficient removal of cuttings (Denney, D 2020).

6. Logging

6.1 Logging while drilling (LWD)

To avoid severe hole cleaning problems in deviated wells it is important to detect risk factors early and avoid accumulation of sediments in the well. Deviated wells are generally considered to wells with inclination below 80º. Early detection gives drilling operators the opportunity to regulate factors affecting hole cleaning performance such as drill string rotation, rheology of mud, flow rate, and drill string eccentricity. Accumulation of cuttings and pack off will happen in deviated wells if complete hole cleaning is not performed during drilling and could lead to several drilling problems such as stuck pipe, formation fracture, cutting accumulation, hole "pack -off" or excessive ECD. Transportation of cuttings to surface is heavily dependent on cuttings size, geometry, and hole angle. Logging while drilling (LWD) in deviated wells is an important tool in automating processes and detecting changes in drilling fluid. Deeper and less accessible wells increase the demand for LWD too since changes in the carrying capacity and hole cleaning will be detected later in these wells. The information gained from LWD is still not considered to worth the cost and common practice is still "blind" drilling, especially true for high temperature, high pressure formations

(HPHT) and logging equipment is prone to damages in these formations and the measurements sensor being unprecise in these environments (Chen, J et al. 2021).

6.2 Drill stem testing

Technology in the field of formation evaluation is in rapid the last 50 years. Drill stem testing (DST) was the pioneer in the well-testing hardware. DST hardware progressed into tools connected to the drill stem and used for testing the formation shortly after drilling. Today the testing of the formation is done while drilling. Wireline formation testing (WFT) was another innovation being able to perform pressure tests in a matter of minutes and quickly displaced drill stem testing. The quicker feedback from the well gives the operators the ability to adjust the drilling according to the results obtained. Today most oil companies have teams of experts using remote software to monitor the results from WFT. Formation testing while drilling (FTWD) started to become more popular and adopted to drilling practices in the early 2000’s. Testing formation activity while drilling has been a massive leap forward in guiding better drilling decisions. Most challenging part is for the tool to withstand the conditions that occur while drilling. The tools must be able to withstand high temperatures and pressures deep into the well while we are drilling. Early adaptions of logging while drilling (LWD)-tools were adaptations of formerly used WFT-tools. This innovation gives us the ability to get feedback from ongoing conditions in the formation related to porosity, resistivity, acoustic waveform, hole direction and weight on bit (WOB). This information is being relayed through pulses in mud column. Providing us with a tool that provides us with real time information from a tool attached deep in the well near the end of the drill string. LWD can be separated into several different techniques.

6.3 Measurement while drilling (MWD)

Five of the most common techniques used to obtain information regarding the formation are induction, propagation, multiarray propagation, acoustics, nuclear magnetic resonance (MWR) and nuclear logging. The last decades measurement while drilling (MWD) has played the major role in borehole surveying. It does however only do the surveying under static conditions and cannot be done while drilling. Dynamic survey while drilling could eliminate the survey-related rig time per survey, reduce the associated drilling risks and improve the efficiency of the drilling operations. Conventional MWD-tool usually takes 10-15 minutes to survey each stand. The process adds 8-10 hours of rig time per well and the time exposure could increase the risk of stuck pipe in deviated wells.

6.4 Induction logging

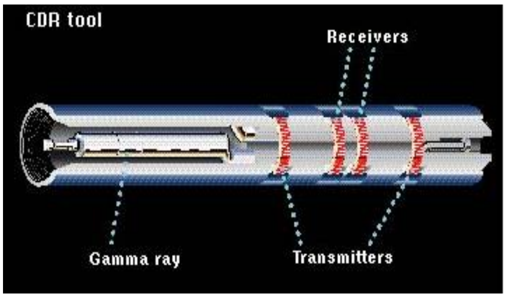

Figure 4 Illustration of a CDR-tool, https://mlp.ldeo.columbia.edu/wp-content/uploads/2016/06/cdr-1.jpg

Induction logging is performed when bottom hole assembly (BHA) is pulled or surged in the well. This movement and the changes it induces is measured by a compensated dual resistivity (CDR)-tool which uses a 2-MHz electromagnetic wave to measure the difference between phase shift and amplitudes measured downhole. CDR-tool also contains equipment to measure the natural gamma ray emission from the formation. Gamma ray emissions from the formation may give us information regarding clay typing, mineralogy and detection of ash layers. Determining clay type is due to the presence of the radioactive elements potassium and thorium. Carbonates usually display a low gamma ray signature, deviation from this in carbonate layers may indicate the presence of potassium due to algal origin or presence of glauconite. The presence of uranium is associated with organic matter. Giving us feedback on the mineralogy of formation. Detection of ash layers is from the ratio of Thorium-Uranium with a given interval since ash layers often contain more thorium. Resistivity measurements give information about porosity, density, lithologic boundary definition and textural changes. Sediments that do not contain clay or other conductive minerals we can use Archie's law, since it relates the resistivity to the inverse power of the resistivity.

6.5 Archie's law

"The minerals comprising a rock are almost always electrical insulators. Thus, electrical conduction occurs because of the moisture contained within the pores of the rock or the soil. The resistivity of soil or rocks depends on several parameters. These include the clay content, moisture salinity, degree of saturation of the pores, and the number, size, and shape of the interconnecting pores. For soils, the degree of compaction (influencing porosity) is also an important factor."

(Louie, J, 2014)

$$S_w = \sqrt[n]{\frac{a * R_w}{\Phi^m * R_t}} \; Eq.4$$

Archie’s law can also be used in determining the density of the rock through velocity reconstruction. These are called pseudo density or pseudo velocity logs and can be useful in indicating the characteristics of the formation over intervals where we have no other logs or unreliable logs. Archie’s law assumes that the rock-matrix are non-conductive and formations containing sandstone with clay minerals this assumption does not work and Waxman-Smits’s equation should be used. Combining the resistivity, acoustic and velocity logs is useful in defining lithological boundaries. For example, decrease in resistivity towards the top of a carbonate unit, coupled with a decrease in velocity are typically observed.

Boreholes containing oil-based muds or in air-drilled boreholes electric devices do not work properly since these are nonconductive conditions. Induction transmitter coil is driven by an alternating current that creates a primary magnetic field around the transmitter coil. The primary magnetic field causes eddy currents to flow in a continuous circular distribution centred around the borehole axis. These eddy currents are proportional to the formation conductivity, and creates a secondary magnetic field, which induces an alternating voltage in the receiver coil. Since the transmitter uses alternating currents phase shifts may occur between the transmitter current and current density in the formation and increases with distance into the formation. Induction tools try to measure the part of the voltage that is exactly 180° phase shifted from the transmitter current. Newer induction tools also try to measure the phase shift of 270° from the transmitter current. The main challenge is determining where the measurement/signal is coming from.

Propagation measurements are made by subtracting the phase shift and the attenuation of the voltages captured at the two receivers. Attenuation and phase shifts are proportional to formation conductivity. Propagation measurements can be used to generate resistivity logs. These measurements must be adjusted according to roughness of the borehole. Two separate measurements are used measurements called relative phase shift (RPS) and resistivity from attenuation deep (RAD).

Multiarray propagation tool consisting of an array of transmitters and receivers whose signal are recorded separately and combined by software. Typically, 5 transmitters emit a signal and the phase shift and attenuation between the two receivers are recorded. The phase shifts are then with the help of the software combined to produce borehole-compensated logs with different depths of investigation and radial resolution. Different version of this tools is produced by Schlumberger, Halliburton, and Baker Hughes, but all these multiarray tools uses 2-Mhz and is a replacement for the formerly used CDR-tool.

6.6 Acoustic logging

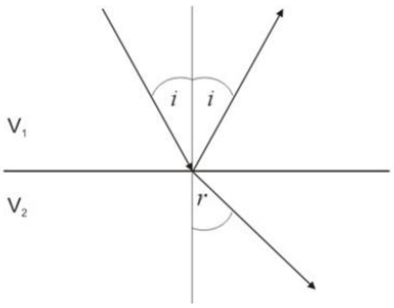

Figure 4 Acoustic waves refraction trough 2 mediums

Modern LWD also contain an acoustic part. The acoustic log measures the travel time of an elastic wave through the formation. This information can be used to derive the velocity and provide information to derive the porosity of the formation. A recording is often done of the travel time of the wave versus the depth of the well. Acoustic waves and the characteristic of the formation is explained by how the acoustic signal and how it behaves going through different mediums. Propagation happens due to the elastic nature of rock formations. The measurable properties for acoustic waves are velocity, amplitude, amplitude attenuation and frequency. The velocity of the acoustic wave is determined by lithology, cementation, clay content, texture, porosity, pore-fluid saturation and composition, overburden-and pore-fluid pressure and temperature. Snell’s law describing refraction between two mediums is an important equation in deriving useful information from the formation. Knowing the speed of acoustic waves in the initial medium, angle of incident, angle of retraction or speed of acoustic waves in the second medium is related through Snell’s law as shown in equation 2 and illustrated in figure 2. Knowing the speed of the medium could give us an indication of what kind of rocks we are dealing with.

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} \quad Eq. 5$$

7. Laminar vs turbulent flow

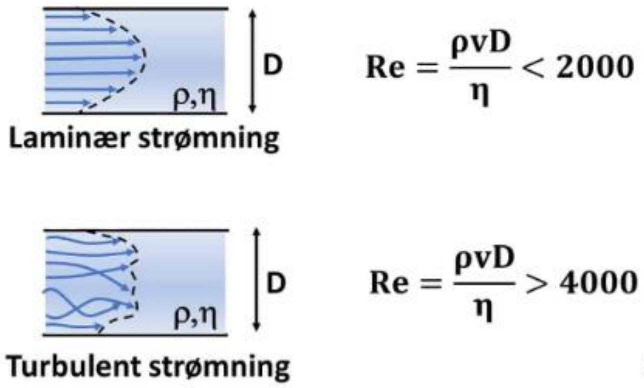

Figure 6 laminar vs turbulent flow

The flow regime around the drill string plays an important role in effective hole cleaning. Flow regimes are often characterized as either laminar or turbulent. Laminar flow occurs when the fluid flow in parallel layers with no disruption between them and Reynolds number for laminar flow should be below 2000. The Reynold number gives us a mathematical description which helps us predict the fluid flow pattern. Gives the ratio between inertial and viscous forces in the fluid, describing the flow patterns in pipes and is therefore a highly beneficial formula, commonly used in engineering. Higher number indicates more turbulent flows, while lower numbers indicating a more laminar flow pattern. Turbulent flow is wanted in horizontal and deviated wells. The different flow paths in a turbulent flow consisting of fluid moving in different directions. The increased turbulence in water often gives a bigger diameter around the drill string with more water activity capable of pushing cuttings back into the fluid flow. Making the water able to whip up cuttings that dropped out earlier forming a cuttings bed. Reynold's number characterizing turbulent flow are above 4000. Numbers used to characterize the different flow states will vary depending on literature and should be taken into consideration when discussing fluids.

Theory

Monitoring the hole cleaning performance in deviated wells are essential. Known indicator for the cleaning performance is looking at the volume of cuttings returned to mud tanks compared to the ROP. Low volume of cuttings returning to mud tanks, while high ROP indicates insufficient hole cleaning. The size and shapes of the returned cutting could also give an indicator of hole cleaning, if the cuttings returned are smooth, round, and small it indicates more times spent in the well. Increase in torque or drag readings should be monitored since they give information about the conditions in hole and can help us avoiding stuck drill string due to accumulation of cuttings. Decrease in torque could lead to inhibition of the necessary rotation speed of drill string to aid the removal of cuttings bed. The process of looking at the returned cutting has been taken even further by Chen, J et al. “Valuable cuttings-based petrophysics analysis successfully reduces drilling risk in HPHT-formations” where they look at changes in mineral composition, color, shape, size of the cuttings and to predict or gain information on formation being drilled where logging is not possible, instead of drilling completely blind. Giving better and more reliable information about depth of cavings, composition of rock and strength of formation at different depths based on surrounding formations (Chen, J et al. 2021).

8.1 Computational fluid dynamics

Inefficient hole cleaning is the main cause of problems associated with directional drilling such as stuck pipe, premature bit wear, slow drilling, formation fracture, excessive torque and drag on drill string, difficulties in logging, difficulties in setting casing. Several papers are therefore looking into and understanding the behaviour of cuttings by computations and simulations. The paper “Cuttings transport behaviour in directional drilling using computational fluid dynamics (CFD)” tries to make a model based on the work of several former studies on deviated wells for different inclinations. Behaviour of the cuttings and the effect of different parameters may be different according to angle of inclination, such as the bigger sized cuttings may be easier to transport out from some wells than the smaller lighter particles (Basal, AA 1995). Smaller particles seem to be more cohesive and stick more easily to drill pipe. Making it even more difficult to release pipe should a stuck-pipe situation occur in a well with more fine-grained particles. It should be noted that different papers still argue regarding if smaller particles really are harder and under what conditions this statement is true. Experiments has been conducted looking for better understanding of the behaviour of cuttings in the paper "Transport of small cuttings in extended-reach drilling" (Duan et al. 2008). Using mathematical modelling to develop correlations for cutting concentration and bed height in annulus for field applications. Results from the mathematical models with experimental data indicates that smaller particles are easier to transport in vertical wells, but more difficult in inclined wells (Parker, DJ 1987. Larsen, TI 1990). In wells or situation with no drill pipe rotation experiments has shown smaller cutting to be easier to transport for all angles. Needing lower minimum transport velocity (MTV) for smaller cuttings. Bed erosion tests in horizontal annulus showing that 2 mm particles were easier to erode and lift from the cuttings bed than the larger 4 mm particles (Ford, JT et al. 1990. Peden, JM et al. 1990. Martin AL, et al 1996).

8.2 Size of cuttings

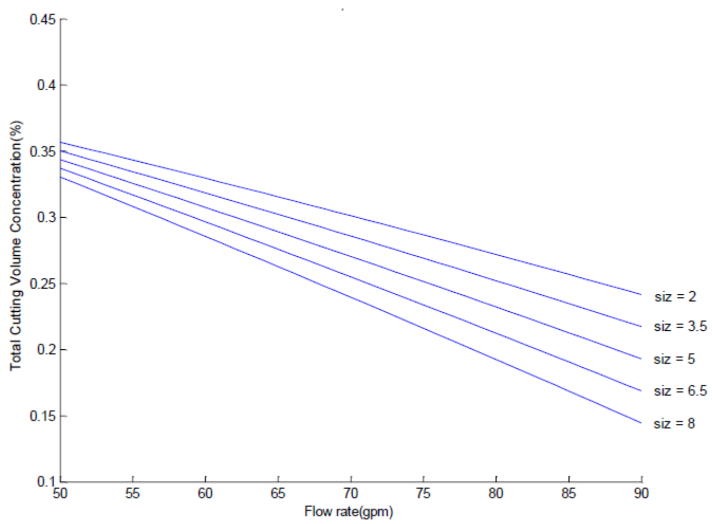

Figure 6-hole cleaning with 60 degrees inclination under different flow rates (Ammana et al 2016).

Smaller cuttings seem to be easier to transport in high viscosity muds, while the opposite seems to hold true for low viscosity muds. Viscosity is not solely responsible and factors such as flow rate, flow regime and angle of inclination play a key role. Other theorizes that there exists a certain size of cuttings that require the maximum transport velocity under certain conditions. Experiments showing that smaller particles are easier to clean out when the particle size is below 0.76mm, but harder to clean out when for size increases above 0,76mm. In horizontal pipe experiments the critical velocity for rolling increased sharply with particle size particle sizes up to 1,5mm with a flattening or decreasing in critical velocity for particles above 1,5mm. In experiments done by Amanna, B et al 2016 the same relation was shown for deviated wells. Figure 6 showing lower concentration of larger cuttings with increased flow rate. In this situation it was assumed that the higher flow rates create a more turbulent flow, which is more efficient in lifting larger particles. The observation held true for different sized well diameters.

A new method to determine friction factor of cuttings slip velocity calculation in vertical wells using neural networks was used to anticipate the shape of the cuttings. The model uses inputs as common logarithm of Reynolds number and sphericity of particle, giving a more accurate friction factor. This leads to more accurate description of the slip velocity and gives us more accurate cuttings transport velocity. Leading to a more accurate parameter for describing the efficiency of cuttings transportation and has been integrated into CORVA AI platform which is a real time drilling engineering system. Model has so far not been integrated for deviated nor horizontal wells (Kamyab, M et al 2016)

Experimental study on shape of drilling cuttings which caused poor transport efficiency that was caused by a parabolic share of laminar velocity regime and the effect of unbalanced forces from the drilling fluid (Williams & Bruce, 1951). Test of more than 2000 dynamic particles carrying test with 13 different drilling muds 52 different particles all with different size and shape. Finding a relationship between slip velocity, march funnel, yield point and mud weight (Hopkin, 1967) and later correlations in their relationship and effect on hole cleaning performance (Moore 1997, Larson 1997 and Malekzadah 2012).

8.3 Angle of inclination

The graph shown in figure 7 vary depending on angle of inclination used during the experiment. They tested for several different angles and with inclination between 30-60 degrees. The fluid used in the experiments were pure water, and the relationship observed might be different in a well situation, since drilling muds used often have properties that water does not in carrying away cuttings from the annulus. The result from the experiment was used to provide data for computational fluid dynamics. A computer model mostly focusing on flow rate, inclination, cutting sizes and drill pipe rotation (RPM) as the most important parameter were then used to simulate expected cuttings concentration in the annulus around the drill pipe. Simulated concentration where lower than the results from the experiments but could be a useful indicator or tool in assisting the drill crew. More experiments and more parameters are needed for more precise

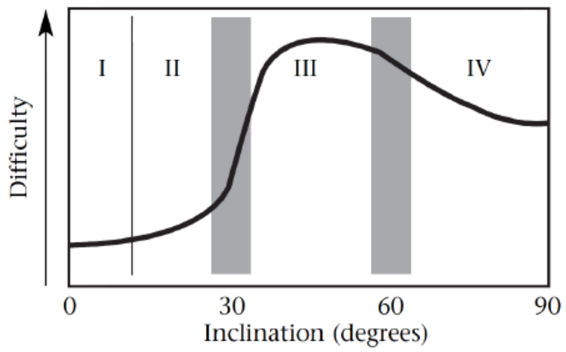

Figure 7 difficulty of efficient hole cleaning for different inclinations (Amanna, B et al 2016) calculations. This experiment was done using water and not drilling fluid, and the rheological properties of the drilling fluid would affect the removal of cuttings (Amanna, B et al 2016).

8.4 Drill pipe rotation

Experiment on transport of cuttings based on size was only looked upon in the paper "Transport of small cuttings in extended-reach drilling" where they discussed the difference in carrying capacity of water to solutions containing polymers, specifically poly anionic cellulose (PAC). Addition of PAC to the water-based muds used during the extended reach drilling heavily improved the hole cleaning efficiency of smaller cuttings. They tried to create a mathematical model to understand the correlations for cuttings concentration bed height in annulus for field applications, specifically developed for small cuttings to get better design of extended-reach drilling. The study looked at pipe rotation effects with different drilling fluids. Smaller cuttings were more efficiently cleaned with the PAC-mud than with just water, while for larger cuttings above 1.4 mm there was not a significant difference. The difference between water and PAC-solutions where even greater if no pipe rotation was present, with only fluid flow rate being the driving force. Figure 8 is meant to illustrate how the cutting bed adapts in presence of drill pipe rotation and how this may push cuttings back into circulation while pipe rotation is present. The observed cuttings bed in annulus were smaller in the tests ran with PAC, but just marginally better than pure water. Same trend as indicated by a lot of other literature were also observed here in concern to cuttings bed, raising the pipe rotation from 0 RPM to 40 RPM significantly reduced the cutting bed. Further increasement did remove more of the cuttings bed, but with diminishing returns. Their new model significantly improved, where their last model overpredicted cuttings bed with up to 100%, their new model with respect to bed height was mostly within 10% of the experimental results (Duan, M et al. 2008,2014).

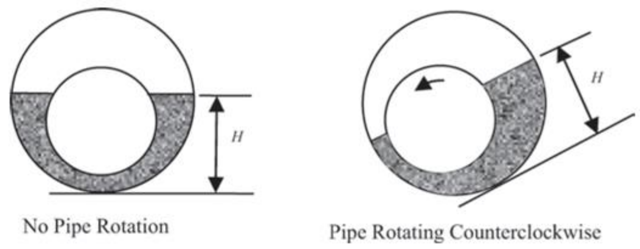

Figure 8 Effects of pipe rotation on the cuttings bed (Duan et al 2014)

8.5 HPHT-conditions

WBM may lose its properties under HPHT-conditions. Simple experiments were done with adding "Multiwall Carbon Nanotubes" (MWCNTs)-additives to water-based mud to see if it could hold up to OBM under more extreme conditions, with the use of a HPHT viscometer. Yield point and gel strength of MWCNTs were higher than that of most conventional WBM. It kept its rheological properties under the conditions. They conclude that they may be an alternative for certain HPHT-conditions with regards to the environmental impact and cost of OBM.

Another alternative too finding new polymers for WBMs in HPHT-conditions are more environmentally friendly OBMs, and one of the promising alternatives has been jatropha oil.

Samples	Density	Apparent viscosity	Plastic viscosity (cp)	Yeild point (lb/100ft^2)	Gel strenght	pH
Diesel based mud	0.84	75	15	120	48	8.2
Jatropha bio-diesel based mud	0.96	21	6	30	29	8.2

Table 1 Rheological properties of diesel and jatropha-based muds (Fadairo et al. 2013)

Table 1 shows the rheological properties of diesel and jatropha after being mixed equally. The water oil ratio was 36% oil and 64% water, 50g bentonite with small adjustment in weighting material. 166 grams for the diesel and 160gram for the jatropha-based mud. Viscosity properties of the jatropha being significantly lower than the viscosities for diesel. Both were then tested for cuttings carrying index, where jatropha oil scored higher than the diesel-based mud. Indicating its potential for more efficient removal of cuttings, but drilling cuttings had detrimental effect on the rheological properties of jatropha-based mud. Additives might be able to reduce this effect and better understanding of the chemistry is needed. The observed pressure loss from using a jatropha-based mud also resulted in a significant lower pressure loss than the diesel counterpart, which attributed to lower plastic viscosity with jatropha oil.

	Diesel based mud	Jatropha biodiesel mud
CCI	15.901	19.067

Table 2 CCI for diesel and jatropha, (Fadairo et al. 2013)

Pipes	Diesel based mud	Jatropha biodiesel based mud
Drilling Pipe	829	227.39
Drilling Collar	177.35	173.75
Drilling Collar (open)	161.35	158.15
Drilling Pipe (open)	14.1	13.81
Drilling Pipe (cased)	9.28	9.10
Total	1191.98	706.45

Table 3 Pressure loss with diesel and jatropha-based mud (Anawe, P et al 2014).

Its behaviour during shear rate and temperature was the topic of discussion in another paper, where the authors also included groundnut oil as potential substitute. During the different test run in this paper, it demonstrated over several different temperature ranges from 60-100° Celsius that jatropha oil was more shear-thickening than the diesel counterpart. Another property of Jatropha oil is that

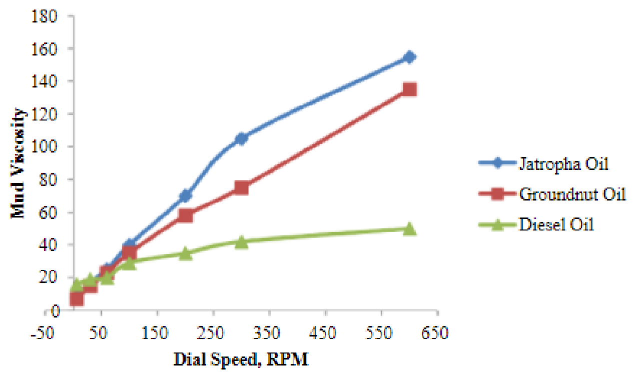

Figure 9 viscosity parameters under differing RPMs, Anawe P 2014

it is more shear thickening than diesel, commonly considered an undesirable trait for drilling fluids This was demonstrated in an experiment and the results can be observed in Figure 9. (Wardana, ING 2010 and Fadairo, AS et al 2013, Anawe, P et al 2014 and Abduo, MI et al 2016))

8.6 Drilling parameters affecting hole cleaning

The most common input parameters in determining ROP are rotatory speed (RPM), weight on bit (WOB), formation properties, depth, flowrate, mud properties, torque, and standpipe pressure. It was also showed in "Drilling in the digital age: An approach to optimizing ROP using machine learning" (Batruny, P et al. 2019) that the type of bit and bottom hole assembly influenced the ROP. The model was based on historic data. Another advantage by creating a model is the fact that there is usually some distance between the logging tools and where the formation is being drilled. Machine learning could give us better real-world data from the well by looking at lagged information from logs. The model took simple controllable parameters as WOB, RPM and mud flow as controllable parameters. It was tested out in four different ultradeep water wells in Gabon, West Africa. Was later tested in nine different wells of various complexity, from different fields and regions. Simple adjustments as more WOB or increasing the RPM based on the computer model was shown to increase the ROP. Calling it a successful application of a one-size fits all ROP optimization model for drilling operations (Robinson, TS et al. 2022).

Hussaini & Azar (1983) paper describes transport of cuttings if annular velocity is less than 120ft/min and model by Zeidler (1974) showing that annular velocity of 164ft/min were required to clean two wells in Canada with just water as fluid. Assumptions made in the model were that CCA should not exceed 5% and combined with CCI could be used to optimize the ROP.

8.7 Mathematical modelling of drilling process

Adaption of new technology and developments in the petroleum business has generally been slow. Automating more processes based on recent developments could aid the drilling crew and cut the costs for the companies doing the drilling with increased rate of penetration and reduce the downtime or need for sweeping pills to clean the hole. This would require real time sensor readings and inputs. Examples of where this has already been done is the paper by Mohammed Al-Rubaii et. Al (2021) “Real time automation of cutting carrying capacity index to predict hole cleaning efficiency and thereby improving well drilling performance”. Automating more of decision making in drilling could increase the ROP, reduce risk and cost by giving a more reliable decision-making process. Mr. Al-Rubaii wrote a paper called “A new robust approach for hole cleaning to improve rate of penetration”. Looking for a more efficient way of giving feedback to the drilling crew based on mathematical formulas and specifically the carrying capacity index (CCI) and cutting concentration in the annulus (CCA). Transport ratio (TR) is relation between cutting/slip velocity to annular velocity. Useful for describing the hole cleaning efficiency. Slip velocity is influenced by size, density, and shape of cutting. Rheology of the mud affects this parameter and can be adjusted trough adjusting density or velocity of the mud. Equations are needed to estimate slip velocity during drilling to help describe more complex flow behaviour. Suggested ratio is that annular velocity of drilling mud should be 1.2 that of the settling velocity to reduce accumulation of cutting in the well. Can be used to find the optimum flow rate and drilling parameters for efficient hole cleaning.

8.8 CCI and CCA for horizontal and deviated wells

Cutting concentration is a function of many parameters and can be given by the following equation:

$$\frac{V_b}{V_W} = f\left(\theta, v, \omega, \rho_s, \rho_l, \mu, D_{hyd}, g, d_c\right) Eq. 6$$

With the use of 25 groups of data (25 runs) and using multi-variable regression technique the following formula was deduced to describe cutting concentration in the well. Adjusting the impact of each parameter do more closely resemble the real-world impact of the different parameters. The impact of the different parameters would be different according to what data set you are using, and the formula deduced underneath is not a universal formula but correct for the given situation based on their experimental results. They used a design of experiments (DOE)-algorithm to aid in this process. Its intention being systematic, efficient method enabling them to study the relationship between multiple input variables and output variables.

The mathematical models used in computation model were based on Bucking-π theorem to find an empirical correlation for estimating cuttings concentration. The theorem is useful method for computing sets of dimensionless parameters from variables. This gave the following result for based on diameter of pipe for the Khartang-field used in this experiment as a model.

$$\frac{V_b}{V_W} = 7{,}9664 * (\frac{\rho v D_{hyd}}{\mu})^{0{,}17759} * \left(\frac{v^2}{g D_{hyd}}\right)^{-0{,}060079} * (\theta)^{-0{,}009657} * \left(\frac{d_c}{D_{hyd}}\right)^{0{,}92395} * \left(\frac{\rho v d_c}{\mu}\right)^{-1{,}0048} * (\frac{\omega D_{hyd}}{v})^{-0{,}060668} \quad Eq.7$$

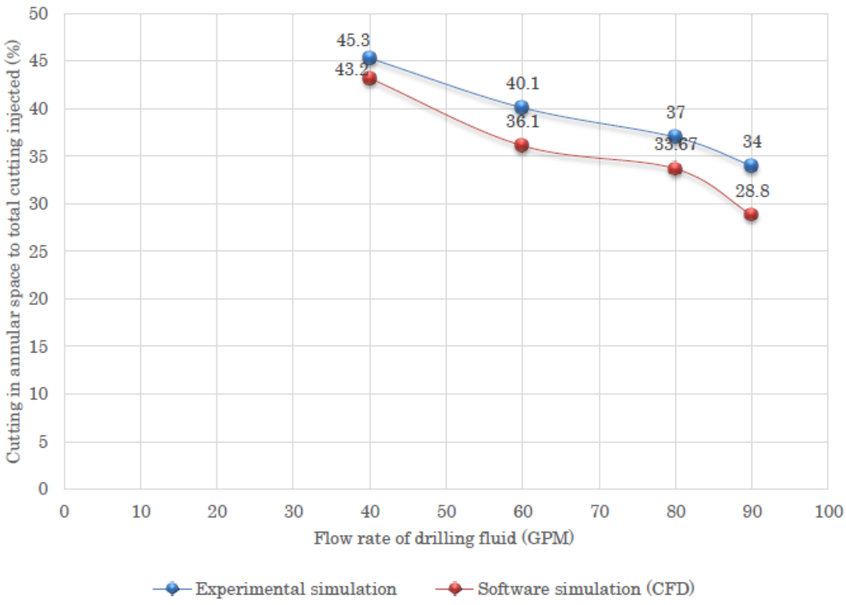

Figure 10 Cutting in the annular space, experimental vs software data (Amanna, B & Movaghar, M 2016)

The computer then used the equation 23 to estimate cutting in the annular space for different flow rates. Software data was then compared to experimental data. Simulated cutting concentration changed in accordance with what they observed during experiments and indicates simulations closely representing real-world wells could be within reach. The computational fluid did the exact same values as observed during experiments, which is to be expected since it only simulates real-world experiments and is only as accurate as the equation we use and the weighting we give the different parameters in the equation. Weighting of the different parameters will probably vary from reservoir to reservoir. These experimental studies could aid choosing the correct mud under HPHT-conditions (Amanna, B & Movaghar,M 2016).

Carrying capacity index (CCI) is an important parameter for how much time the cutting has spent in the well and how efficient the cleaning has been. Ideal clearing of cutting would contain cutting with sharp edges. More time spent in the well, would mean the cuttings has been exposed to more friction, and the sharp edges would have been worn down. Round edges would therefore more tumbling, and time spent in the annulus. This extra time spent in annulus would wear the cuttings and disintegrate them into smaller pieces which can change increase and change the composition of the drilling fluid and its properties. True for both vertical and deviated wells. CCI has been determined by observing hole cleaning conditions on many rigs over several years and the models seems to work for both water and oil-based muds. Parameter used to estimate CCI are mud weight, annular velocity, and characteristic viscosity. Cuttings are looked at in the shaker screen and changes in morphology could there give us a good indicator for changes occurring in the well. Ratio is expected to be 1 or greater for wells with efficient hole cleaning. In situations where the cuttings are rounded and smaller CCI value is normally considered to be below 0,5. In wells with inclination above 26° modifications to the formula for CCI must be done and was developed by Tobenna (2010).

Cutting concentration in the annulus (CCA) gives an indication of how much of the cutting are in the annulus while drilling. A lot of work has been put into getting mathematical formulas describing the accumulation or concentration of cutting. As a rule of thumb, the concentration should not exceed 5%, some operate with up to 8%. Experiences from the laboratory testing shows that if the flow rate is high enough cuttings will be removed for any fluid, hole size and angle. Flow rate, high rotary speeds and backreaming are all efficient tools to aid the cleaning of annulus.

$$CCA = \frac{ROP * OH^2}{1472 * GPM * TR} \ (Eq. 8), Mitchell\ (1955)$$

$$CCI = \frac{MW * K * Av}{400\,000} \ (Eq. 9), Robinson\ and\ Morgan\ (2004)$$

$$CCI = \frac{K * TI}{3585 * A_a * RF} \ (Eq. 10), Tobenna\ (2010)$$

Equation 9 can only be used in vertical wells or for inclination between 0-25degrees. CCI for deviated wells beyond this the CCI must be modified. A relationship between RF and CCI was found and equation 10 was found by Tobenna and can be used to estimate CCI for higher inclination than 26 degrees. For efficient and precise calculations information gained by simulations or LWD-tools regarding parameters affecting CCI and CCA are extremely important. The whole paper argues for a model based on constant feedback of information, which we can calculate in real time by a computer.

Al-Rubaii's automating models that can be used to evaluate the hole cleaning performance in the wellbore from operational parameters to achieve higher ROP. Important focus on data analytic processes (data preparation, data processing, data transformation, data mining and data evaluation) giving a strong and trustable model for conditions in the wellbore. The object of the paper was to get a real time evaluation for hole cleaning efficiency, optimize well drilling and ROP while minimizing hole problems (stuck-pipe, possible pack-off, excessive ECD, formation fracture and cutting accumulation). The automation and development in the latest paper was based on former models and automation Al-Raii had done in two former papers. His paper from 2018, "A new robust approach for hole cleaning to improve rate of penetration" was based on more deductions and mathematical models describing relations in rheology and their effect on the efficiency in hole cleaning. Data from former wells with regards to mud rheology and drill pipe rotation are valuable information to optimise our models

Optimizing ROP with regards to the CCA and CCI to optimize the drilling rate using the drilling specific energy (DSE), selecting optimal drilling parameters using trial and error. "Automated evaluation of hole cleaning efficiency while drilling improves rate of penetration" is a paper discussing this model to increase ROP. Describing new hole cleaning automated models and indexes that were developed to monitor, optimize and control well drilling and operations performance. Useful for predicting the minimum annular velocity and cuttings bed thickness in horizontal and inclined wells. The goal of the paper was to automate CCI by using transport ratio, mud weight or drilling fluid density while drilling.

$$DSE = \frac{4 * WOB}{\pi * {D_B}^2} + \frac{480 * RPM * TRQ}{{D_B}^2 * ROP} - \frac{3189335 * \ HHP_B}{{D_B}^4 * ROP} \ (Eq. 11), Khamis \ (2013)$$

The automation of the process and live feedback of information would ideally also aid the selection process in most effective sweeping pills. Pressure sensors in the heel and toe to aid the selection. The best pill is often unique for each well and for different phases of the drilling. Vertical wells often use high viscosity sweeping pills, while choosing the correct sweeping pill in deviated wells are a more complex and guidance on best practice vary in literature. A lot of the logging equipment currently available also have problems in the drilling conditions experienced during deviated drilling compared vertical wells, and the amount of information being relayed back to the drilling crew is less than during vertical drilling. This increases the risk for complications during drilling and makes the decision-making process difficult and inefficient increasing the cost for the companies involved (Czuprat, O et al 2020).

8.8 Hydraulic optimisation

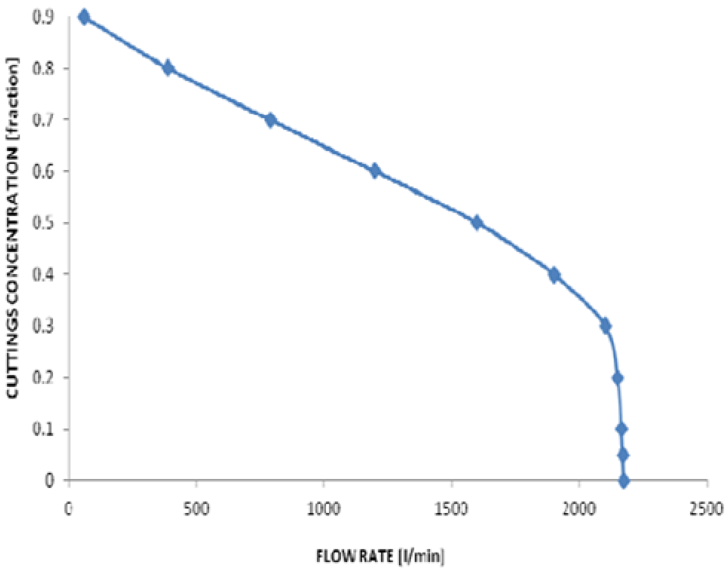

Figure 5 Cutting concentration with regards to flow rate (Ogunrinde, JO & Dosumno, A 2012)

Hydraulic optimization is another factor in achieving efficient hole cleaning. Determining the optimal pressure drop across the bit, optimum jet impact force at the bit could be used to optimize the flow rate for hole cleaning. This information could be used to find the correct pumping pressure to achieve the optimized flow rate in the well. Finding the optimal flow rate is essential due to it together with drill pipe rotation often being considered two most important factors for good hole cleaning in deviated wells. Cutting's concentration generally decreases as the flow rate increases. The increased flow rate and lower cutting concentration makes it easier for the drilling fluid to transport cuttings. The paper "Hydraulic optimization for efficient hole cleaning in deviated and horizontal wells" describes the effect of flow rate on hole cleaning. Flow rate is the dominating parameter on cutting bed development. Increased flow rate gives reduced bed development. Turbulent flow is better for preventing bed development in inclined or horizontal wells. An increase in the performance index (n) increases fluid flow rate thereby decreasing the cuttings deposition in the hole. High circulation rate is essential in ensuring cuttings removal. The determination of minimum annular requirements will help to predict the flow rate that will be needed to ensure proper hole cleaning. In their paper they find a mathematical model to estimate the flow rate that will effectively remove cuttings in inclined or horizontal wells (Ogunrinde, JO & Dosumno A 2012, Mishra, N 2007).

Downhole vibration is associated with ROP and can lead to failure of the bottom hole assembly (BHA)-tool. Drilling with polycrystalline diamond compact (PDC)-cutter vibrational problems are commonly experienced, especially in wells where underreamers are used to enlarge the well beneath the casing. The vibrations have also shown to be troublesome in directional drilling. Focus of several papers has been to control bit aggressiveness and subsequent vibration induced at the cutter rock interface to achieve a balance between ROP and vibration as it responds to WOB. When cutters are not in contact with the formation this created force imbalances. Stick-slip has plagued the drilling industry for decades and innovations within optimized drilling parameters, bit technology, downhole technology and surface systems has been done with intention of solving this problem. These vibrations can be difficult to identify from surface reading and require additional downhole sensors. Several papers from S, Chen has been introduced discussing these challenges. Increasing the aggressiveness of the cutting structure of the PCD bit within critical sections is found to be helpful to mitigate bit stick/slip vibration. The issue can also be split into two different causes, cutting action induced or friction induced stick/slip. It is therefore crucial to determine if the vibrations are caused by friction forces, cutting action or a combination of the two. Cutting action induced vibrations seems to be controllable trough good understanding in the relationship between WOB, ROP, RPM and TOB. In the paper “Identification and mitigations of friction – cutting action-induced stick/slip vibrations with PDC-bits” has a good theoretical part regarding to this and claim to show that the vibrational forces are therefore directly related to bit direct energy (DE) A more aggressive cutting structure can result in less torque, and consequently greater average DE. (Dao, 2019, Jaggi, 2007 and Chen, 2013,2014,2020).

$$E_s = \frac{WOB}{A} + \frac{120\pi * RPM * TOB}{A * ROP} \quad Eq.12$$

$$DE = \frac{\sigma_{rock}}{E_s} * 100\% \quad Eq.13$$

8.9 Simple code for illustrative purpose

```
# *Simple coding for drilling

# Parameters used in equations

# PV, Plastic viscosity [cP] *

PV = 32

# YP, Yield Point [cP] *

YP = 33

# OH, Hole section [inch] *

OH = 8

# Aa, annular area [inch], simplified! *

Aa = OH*3.14

# AV, annular velocity mud [ft/min] *

AV = 15

# n

n = 3.32*log((2*PV+YP)/(PV+YP))

# k, consistency index *

k = (511^1-n)*(PV+YP)

# p, density [lb/gal] *

p = 8.33

# RF, rheology factor (hole size, YP and PV) *!*

RF = PV/YP

# TR, transport ratio "Slip velocity to annular velocity"

TR = 1.2*AV

# GPM [Gal/min]*

GPM = 500

# TI, transport index

TI = (GPM*p*RF)/834.5

#RPM *

RPM = 50

# Ab, area of bit = 1.1*annular area, for easy calculation

Ab = 1.1*Aa

# WOB, weight on bit [lbf] *

WOB = 10000


# WOBt, weight on bit over time

WOBt = 0.9*WOB

# K, drill bit dullness and formassion abrasiveness *

K = 0.9

# S, Slide [ft] *

S = 700

# ROP, rate of penetration, Warren 1984 [ft/hr]

ROP = K*((RPM*(WOB-WOBt)^2)/(Ab^2*S))

# Value for CCI, inclined wells, 0.5 or less

CCI = (K*TI)/(3585*Aa*RF)

# Value for CCA, should not exceed 5%

CCA = (ROP*OH^2)/(1472*GPM*TR)

if (CCA>0.05){
  print("Cuttings exceeding clearing capacity")
}else {
  "Keep on drilling"
}
```

Figure 12 Simple code issuing command that "Cuttings exceeding clearing capacity" or "Keep on drilling"

I wanted to write simple code to illustrate how small innovation and improvements can aid the hole cleaning process in wells. Based on the principles of Al-Rubaii, where he used CCA and CCI to optimize the ROP. All my parameters with an Asterisk (*) in them are fixed parameters in my code and would ideally be swapped out with real-time data from the well during drilling. The code calculates cuttings in the annulus based on the parameters and would either give a command to “Keep on drilling” or “Cuttings exceeding clearing capacity”.

Figure 12 uses equation 9 and 10 + a formula for ROP from “Mathematical modelling applied to drilling engineering: An application of Bourgoyne and Young ROP to a pre-salt study”. The use of Tobenna’s equation for wells with inclination exceeding 26 degrees and ROP from a pre-salt study would indicate that the code written to be well suited for drilling in a deviated pre-salt formation.

Real time data would then give constant feedback on hole cleaning is sufficient or if we should act trough steps intended to increase hole the hole cleaning. Changes to the ROP, GPM or rheology of the drilling mud would be easily adjustable changes a drilling crew could make to ensure sufficient hole cleaning. The same way of thinking could be used illustrative example of coding to Eq. 10,11 and 12 regarding energy at the bit-rock interface. Finding the ideal direct energy while drilling if we know the hardness of the rock formation and ability to calculate the direct specific energy more precisely at the bit surface which could potentially lead to faster ROP, less downtime and safer drilling.

8.8 Logging equipment

More accurate information about the formation while drilling has been in the mind of engineers for years. One possibility for innovation is a new FTWD-tool that is attached to the drill collar. It has a snorkel attaching itself to the formation through the mud cake to get a more accurate reading of the formation pressure. Varying success was observed. Result from the FTWD tool was compared to the result from a more commonly used WFT in nearby well in Pantai Field. Formation testing results identified formation markers and the complete logging acquisition during drilling. The pressure measurements, repeatability and accuracy are similar in both testing methods. Main difference being the environment during acquisition being different. The new FTWD tool gave stable result equal to those observed with the WFT. Challenges associated with washed-out borehole had the same impact in both methods. Potential for reduced time consumption with the new FTWD-tool in the utilization of real-time drilling, but cannot do real time fluid sampling or fluid ID-measurements (Manurung, VB et al. 2022 and Vij, J et al 2018)

Vertical seismic profile (VSP) are useful measurements to obtain accurate time-depth pair for time-depth conversion in seismic surveys. In deviated wells the source receiver travel path is not a vertical straight line, but an oblique, refracted path. The effects of anisotropy were formerly not added to models and would therefore not correctly adjust ray travel time and imaging for deviated wells. They proposed a new method to minimize vertical errors for rig source VSPs acquired in deviated wells, with a large source-receiver offset in the presence of varying formations. Good modelling was achieved through careful corrections based on knowledge of the formation (How, et al. 2022)

Methodology

The data collected are based on real-world data from other wells, experimental data, or simulated data. For most of the data collected I do not have the ability to recreate the experiments run or data collected, and this thesis has a weakness in being based completely on work of other people's data. Most of the data is from peer-reviewed papers and wrong assumptions or wrong interpretation of data is hopefully therefore kept at a minimum in this thesis. The collection was done by reading through most of the recent developments. Interpretation of the data collected was difficult due to not being able rerun the experiments or run the computer programs used in the different papers. The methods used in the different papers were well described and could be replicated if time, resources, and equipment are available. The paper is based on available papers, since most of them are peer-reviewed or has gone through screening process before being published. Hopefully indicating that the findings and developments discussed in this thesis is factually correct, with just the importance of the different finds being subject to debate.

The timeline of what being categorized as recent developments is probably different and ever changing according to what field we are discussing. The paper tried to keep the discussion to papers being related to advancements within the topics discussed. Papers from 2019 with regards to computer modelling could be far behind, while papers discussing logging tools from 2016 could still be cutting edge technology. This could therefore feel like repetition of information for someone looking for the newest technologies within their respective fields. Some of the studies are from vertical wells, with direct relation or use in deviated wells. Breakthrough in studies with regards to development in hole cleaning for deviated wells may therefore lead to developments in hole cleaning technology for vertical wells.

Some of the equations discussed in this paper are from experimental models and it is naturally to assume some differences when going from one well to another or changes in rock formation during drilling. For example, the ROP-equation used in the illustrative example came from a presalt study. Further showing the capability and flexibility of computers. With the correct information either from logging or anticipating changes from lagged information, the computer could easily change the formula in an instant when going from one rock type to another within the formation.

Data and studies discussed in this thesis is mostly based on the work of published articles widely available. Most of the studies were found through the website www.oneptro.org and www.researchgate.net. The paper focused mostly on studies or papers within the last 5 years and innovative in their approach to developments within the field of hole cleaning technology for deviated wells. One weakness of this paper is the focus on petroleum-based articles contra pure geothermal wells, since most articles discussed are from petroleum-based articles. Developments in hole cleaning technology and the techniques or technology discussed will mostly be applicable to both types of wells. The physical and technical difficulties are similar during the drilling process of the well is similar in both cases.

One of the sources used in this paper were from an anonymous source and credibility of anonymous sources should be taken with cautious. It was a well written paper with good references to known textbooks and peer-reviewed articles.

Analysis

Using real time sensors in drilling and with the help of mathematical formulas we can create code and programs to automate the information coming from the different sensors aiding the drilling crew in the decision making. Having sensors in the mud pump or preferably in the vertical sections or horizontal sections of the well comparing ROP to cuttings in the drilling fluid we could easily deduce changes or problems occurring in the well. Automation of this process could lead to faster decision making and reduce the time it takes from changes in cleaning in the well to adjustments can be done.

The work and developments currently being done shows great promise but taking the work from experiments to real-world data is difficult due the varying conditions during drilling. A lot more could be added in the logging part of this paper to give the reader a better understanding of the petrophysics related to logging-tools. Better descriptions of the innovations and future potential related to this technology can be found in the paper “LWD as the absolute formation evaluation technology present-day capabilities, limitations and future developments of LWD technology” by Jitesh Vij as it describes the potential and current limit limitations of the technology.

The paper could also have spent more time regarding Stoke’s law to better explain the relationship between sedimentation and the rheological properties of the mud. The rheological properties of the mud and their relation to each other is heavily discussed in Al-Rubaii’s paper from 2018 and have additional info on these relations. The forces related to sedimentation is an area where computer modelling would be highly beneficial and experiments show big differences between settling in inclined, horizontal, or vertical wells.

Discussion

Performing the most efficient hole cleaning for deviated wells are incredibly difficult. Improvements in equipment and understanding of the parameters affecting hole cleaning in deviated wells are still needed. Most important parameters affecting hole cleaning from the different literature seems to indicate that flow rate and drill string rotation speed as the two most important factors affecting hole cleaning. The results from some of the studies are probably not as relevant to describing the behaviour of drilling fluid in real-world wells as demonstrated in experiments. Studies referred to in this paper talks about the removal of small cuttings as more troublesome and difficult than larger cuttings. Most of the studies showing this relationship and the difficulty removing smaller cuttings uses pure water as drilling fluid. The addition of polymers as used during most real-world drills makes the transportation of smaller cuttings easier than larger ones. This does not mean that smaller cuttings are not one of the main difficulties in deviated wells but is meant to illustrate the difference between results or models created in lab from the real-data wells. Angle of inclination would also impact the results. Equation 1 related to rheology of the fluid is another example of where the results from lab would differ from the real-world wells, not only since it is based on water as drilling fluid, but since the data used to find the “correct” weighting for the different parameters only holds true for the situation given in the lab, which were under controlled setting and the exact same setup could be run several times. New experiments equipment, techniques or data programs will hopefully aid the process of describing the situation deep in the well under extreme conditions.

Choosing the correct mud for deviated well is a complex topic. It is rarely possible to purely choose the mud that gives the best hole cleaning properties. Finding the correct mud is an intricate balance between economy, environment, and rheology. High viscosity or high thixotropic effects generally considered to aid the hole cleaning in most wells can be detrimental in deviated wells. This is due to the frictional forces involved in deviated drilling, and the choosing a mud which increases the frictional forces in the well or limits the drill pipe rotation or flow rate would increase the risk of drilling problems.

Desired qualities in a vertical well are different than the properties for deviated wells. For a long time, we mostly used oil-based muds in deviated drilling, but improvements and innovation has made water-based muds more commonly used even in deviated wells. The environmental impact from oil-based muds is much higher and has higher requirements for how we handle and processes the cutting coming from oil-based muds. These cuttings will have to handled and sent to special facilities normally on land to remove the remaining oil still situated on or in the rock. We are still looking for potential innovation as more environmentally friendly oils, like jatropha, but most of these alternatives are not economically viable, do not have the right rheological properties or cannot be produced in sufficient amounts.

The agriculture cost is another important factor to consider if we should focus on using more environmentally friendly oils. Production of these take up large areas of farmland, who could otherwise be used to produce food (some of the alternative oils are currently used in our cooking, like sunflower or canola oil), which means the cost of the producing are potentially taking away farmland and forcing farmers to produce products for oil-industry instead of focusing on food production, if the profits from producing oils are much higher. Jatropha oil seeds contains more than 30% oil, and it is currently not being grown for agriculture products. Currently just growing wild in Africa. The seeds are currently used as pellets in ovens or turbines, and there are promising studies showing its capabilities as a substitute in drilling muds. The result from the experiments with jatropha oil seems kind impressive but getting the result that jatropha oil has a higher CCI than the diesel based one. Seems counter intuitive by looking at the rheological properties in table 1. Where significantly higher viscosities for diesel were observed and then in table 2 CCI being higher than the diesel counterpart. Increase in viscosity for jatropha under higher shear rates might not be accounted for giving them greater cleaning during dynamic conditions. Table 3 claims significant lower pressure loss compared to its diesel counterpart is interesting too. Results indicating that jatropha are more lubricating, less pressure loss and better hole cleaning capabilities makes it an exciting innovation if the statements of its qualities hold true.

Improvements in water-based muds for use in deviated has been great and has allowed deviated drilling to be performed in some situations even better than with oil-based muds. The improvement in general have been keeping the hole cleaning properties of WBM, while not having strong gel-building properties. Most of the research and papers focused on in this paper regarding muds look at the addition of newly developed polymers to the water to aid the hole cleaning in deviated wells. Maintaining those properties for some of the more commonly used polymers in vertical wells does not always translate into deviated wells. This is often due to the different physical conditions polymers in the mud are exposed to under deviated drilling. Deviated wells more often being exposed to high pressure or high temperature conditions. Polymers used in vertical wells usually breaks down or changes their efficiency at about 120-150° Celsius. Newer polymers or carbon nanotubes developed for deviated drilling are in laboratory test exposed for temperatures up to 260° Celsius. OBM has generally been used in high temperature conditions, but with these new developments WBM can be adapted to a wider range of well conditions. The use of multiwall carbon nanotubes as an alternative was interesting, but they had no testing of the mud outside the tests performed in the HPHT viscometer.

The mathematical modelling used in a lot of the studies looked upon in this paper has a lot of potential to improve the drilling operations in normal and deviated wells. The work done by Mr. Al-Rubaii in his papers have the potential to be giant leaps forward in our approach to drilling. Unfortunately, the mathematical models are dependent on real-time feedback from real-world and constantly changing conditions down at bit where the drilling is being performed. Getting real-time data on the changing parameters still seems to be several years away, but improvements are constantly being made. Several of the papers looked upon in this paper tries to use artificial intelligence (AI) to solve this challenge. Using the data from LWD-tools they have tried to make the AI capable of predicting changes in the well bore while or before they happen.

Mathematical formulas are based on previous data limited by the understanding and precision of our parameters. An adaptable AI that drills blind, without information about the formation from earlier explorations or drilling operator nearby does not seem feasible. AI as a tool in assisting the operator is currently being used and can be of great assistance in performing faster and safer drilling operations. The success rate of AI in predicting and understanding changes is in many cases better than humans. A famous example is the price of wine. There are very good AIs able to predict the price of wine the following year by looking at weather forecasts, former prices and other parameters affecting wine price. They beat wine experts 90% of the time, but they are beat 10% of the time. In some years the parameters, weighting of different the parameters or a parameter the AI does not take into consideration forces it into a wrong conclusion and the knowledge of the wine experts come into play. The role of AI in drilling can be a great tool in aiding the operators make better decisions. Going from one formation to another one or drilling areas with different properties than the AI or logging has anticipated has been a problem, and the knowledge of the drilling crew plays an essential role in making the correct decision. More computer power could of course be an advantage in the future but does not seem to be limiting factor. Limiting factors seems to be good mathematical models, understanding the changing parameters and for LWD to give accurate feedback to the AI.

The paper which derived an equation for DE were based on the 30 successful runs testing out their model on how to reduce the vibration during drilling. 17 of the 30 runs had a bit design that gave a 45% increase in the DE. Their mathematical modelling was superb on limiting the number of parameters to be considered in the equation. Then later adding a lot of new parameters affecting the vibrational effects through different bit designs seemed counterintuitive. Higher number of runs in equal conditions would be more ideal to understand the relationship between DE and the vibrational effects. One of the designs had six runs, two runs in Oklahoma and four runs in Texas, which is a good indication of how difficult and expensive it so to drill real world wells to gain a more precise mathematical formula or better anticipate the arrival of vibrational effects on the drill pipe leading to achieve more efficient drilling. Small improvements like this could be very beneficial and cost effective for companies that are willing to take on the additional research and getting than informational edge over your competitors.

In the age of digitalization, small informational advantages and technological advantages have proven again and again to give big companies billions in profit. Wall Street has taken it to the extreme, where milliseconds in technologically advantage give them billions in profit each year by having information a little bit quicker than their competitors. Buying up entire building blocks to shoot lasers in a straight line, while the rest of us awaits incoming information from fibre optic cables laying under our roads. Giving them the ability to front run other people's trades, a similar concept to "scalping" known as "payment for order flow", where you buy an item just to sell it someone else for a higher price. Each trade barely making them any money at all, but the accumulation of all those trades resulting in billions.

We have seen exponential growth when it comes to information, and the addition of computers into our world. A lot of the things around us in the world keeps evolving. The computing power has increased exponentially, and we now have more powerful computers in our pocket than those that filled entire buildings just 40 years ago. This tremendous increase in calculation power is hard to visualize. The data power that was onboard Apollo11, the spacecraft that put the first man on the moon in 1969, had less computing power than calculators used in current day elementary schools. Better research to understand the relationship between the real world and our mathematical formulas are essential in advancing our understanding of drilling and efficient hole cleaning. Giving computers real-world data based on lagged information from the varying parameters in the drill during the drilling would be tremendously cost and time beneficial for future drilling operations. Potentially massively reducing the impacts of drilling on the environment as well. Better data from the well, could increase the mud design and modify the mud to the changing conditions in the well like increased sedimentation, ECD or filter loss faster, reducing the probability of drilling related complications. Better mud design could therefore also reduce the need for OBM in drilling operations, with respect to environmental concerns. Other environmental concerns like causing pollution and be damaging public lands would likely be another secondary effect of good drilling practice/knowledge. Once again showing the importance of good logging tools. Any mathematical modelling may never be more precise than the information we put into them.

Conclusion

Controlling the amount of cutting and ensuring good hole cleaning would allow optimization of ROP while maintaining good drilling practice. We are getting better data, better models, and better AIs to aid us in this process. The potential economic benefits will be huge for drilling companies giving faster and more safe drilling. Risks associated with accumulation or inefficient hole cleaning in deviated wells are becoming lower.

Models are becoming closer to describing the reality for most of the parameters affecting the drilling process and hole cleaning. We are getting better at understanding the rheology of mud under dynamic conditions with the aid of computational fluids. Assisting us in the process of finding ideal mud for best hole cleaning under difficult conditions easier.

Designing better logging tools has been a focus area for years, advantages within this field has been slower in some respects that heavily affects directional drilling. Wells are being drilled in more and more extreme situations. Even if there are advancements within the field of LWD, does not mean the same tools to work under the extreme conditions present at the interface of the bit and annular space around thousands of meters below both water and rock. Temperature conditions combined with the pressure pushing the equipment to the limits of its material properties. With the engineering capabilities of the human species, we can overcome these challenges to create more efficient systems. Even a small increasements in the precision of existing technologies may have large value with the advancements withing AI and computer modelling. Giving the ability to adapt to changes before they occur. Their impact on the drilling and correct course of action to optimize the drilling process withing milliseconds. Massively adding to safety of drilling and as an informational tool that can be used by a drilling crew.

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Nomenclature

μ = viscosity of fluid [cP]

A = The cross-sectional area of the hole drilled by a bit [$in.^2$]

A_a = Annular area [$lb/100ft^2$]

A_b = Area of bit [in^2]

Av = Mud annular velocity [ft/min]

D_b = Bit diameter [in]

d_c = diameter of cuttings [m]

D_{hyd} = hydraulic diameter [m]

DSE = Drilling specific energy [psi]

E_s = Specific energy [psi]

g = gravity constant [N/kg]

HHP_b = Bit hydraulic horse power

K = $511^{(1-n)} * (PV + YP)$ [cP]

MW = Mud weight [PPG]

n = 3,32*log $\frac{2PV+YP}{PV+YP}$

OH = Hole section [in]

PV = Plastic viscosity [cP]

RF = Rheology factor

ROP = Rate of penetration [ft/hr]

TI = Transport index

TR = Transport ratio

TRQ = Torque [ft-lb]

v = flow rate [m/s]

V_b = Cutting volume [m^3]

V_w = Wellbore volume [m^3]

YP = Yield point [$lb/100ft^2$]

γ = shear rate

θ = Angle of inclination [°]

ρ = density of fluid [kg/m3]

σ_{rock} = Rock compressive strength [psi]

τ = shear stress

Ω = Drill string rotation [RPM]

Abbreviations

CCA – Cutting concentration in annulus

CCI – Carrying capacity index

DE – Direct energy

DOE – Design of experiments

DSE – Direct specific energy

DST – Drill stem testing

ECD – Equivalent circulating density

FTWD – Formation testing while drilling

HHPb – Bit hydraulic horsepower

HPHT – High pressure high temperature

LWD – Logging while drilling

MTV – Minimum transport velocity

MWD – Measurement while drilling

OBM – Oil based mud

RAD – Resistivity from attenuation deep

ROP – Rate of penetration

RPM – Rounds per minute

RPS – Relative phase shift

TR – Transport ratio

WBM – Water based mud

WFT – Wireline formation testing

WOB – Weight on bit

YP - Yield point

PV – Plastic viscosity