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Hydraulic Evaluation of Drilling Fluid Performance on Hole Cleaning for Different Rheological Models

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Abstract

Bottom hole cleaning is an important function of drilling fluid that needs special attention during a drilling operation. Good hole cleaning results in an increase in penetration rate and, at the same time, reduces the operating drilling cost. One of the effective steps towards reducing operating cost is to have a well designed drilling hydraulics program that will optimize the energy used at the mud pumps. A variety of hydraulic optimization designs are available depending on the cutting structure and the formation to be drilled but a common objective is to maximize the available hydraulics to provide optimum hole cleaning.

Many authors have discussed various ways of effecting proper hole cleaning using different approaches and methods. Fluid velocity, pump rate, fluid rheology, drill pipe eccentricity, pipe rotation and particle settling velocity, among others were used at various times to evaluate effective hole cleaning. The economic appraisal of hole cleaning using hydraulic horsepower and jet impact force by Wright et al (2003) have proved that both can be used for the design of optimum hydraulic programs on the basis of minimum drilling cost.

In this study, basic hydraulic models for vertical oil wells were used to determine the pressure drop in a drill string circulating system and hence, the equivalent circulating density (ECD) using both the Bingham plastic and Power law fluids' rheological models. From the slip velocity relationships, the transport efficiency of the cuttings for both models was determined.

An economic evaluation of the hydraulics from the energy and horsepower requirements for both models showed that the power law fluid model provided a better transport efficiency, and hence more economical in terms of minimum drilling cost.

Introduction

The transportation of drill cuttings from the bottom of the hole to the surface by drilling fluid through well bore annulus is essentially a two phase flow of solid particles (as drill cuttings) and liquid (as drilling fluid). Due to gravitational force, the cuttings have a tendency to slip downward principally by means of their settling velocity.

Accumulation of cuttings at the bottom of the hole, results in cuttings bed formation in drilling operations, which is difficult to circulate out. The difficulty in removing cuttings bed during drilling arises because of the formation of cuttings bed gel due to the drilling fluid interaction with the cuttings in cuttings bed.. The drilling fluid composition can be designed to minimize gel formation in the cuttings bed. At the same time, the drilling fluid properties are optimized to ensure a sufficient shear stress on the cuttings particles to be able to remove the cuttings.

It is due to different severe operational problems associated with insufficient hole cleaning, that much effort and resources have been spent to achieve effective hole cleaning in drilling operations. Poor or insufficient hole cleaning may result in the following difficulties which will increase cost:

a. Lost circulation created by high equivalent circulating density (ECD)
b. Low penetration rate
c. Cutting bed formation
d. Hinder the casing or liner from being run in a selected position (poor cement job)
e. High rotary torque/tight trips

These, in most cases, lead to stuck pipe. Therefore, to avoid increase in cost it is important to use effective operational practice to ensure optimum hole cleaning.

The introduction of jet bits in 1948 reversed the trend towards high circulation rates. Jet bits introduced the need for increased pressure losses through the bit nozzles for adequate bottom-hole cleaning. One way of meeting this need was to reduce pressure losses in other parts of the drill strings by reducing circulation rates. Pressure losses were then increased through the bit by using small nozzle sizes (Moore 1974).

Recommendations to obtain good hole cleaning vary, depending on different experiences or other sources that the recommendation is based. Effective hole cleaning is an important task in directional and/or horizontal well drilling. Under the same drilling condition, directional boreholes require significantly higher flow rates than those of vertical ones in order to obtain the same hole cleaning efficiency. However, in many cases the required flow rates are not practically achievable due to pump limitations and hole enlargement problems.

In this study, two water-based drilling fluid systems (A and B) were used to evaluate for hole cleaning efficiency of a drilled bore hole. Fluid A is characterized by Bingham plastic fluid behaviour, and Fluid B is characterized by Power law fluid behaviour.

Previous Investigations

The parameters that affect the transportation of cuttings in the annulus can be divided into three groups. The first group consists of fluid parameters which include; fluid viscosity, fluid density, and fluid flow rate. The second group consists of cuttings parameters which include; cutting density, size and shape, and cutting concentration in the annulus. The third group consists of pipe rotation, drill string speed and eccentricity in the hole. There has not been any widely accepted equation that can be used to account for the effect of the variables that affect the transportation of cuttings. Hence, the description of the motion of cuttings in the annulus for efficient hole cleaning still remains unclear.

Two common rheological models *(Bingham plastic and Power law)* are often used to describe the viscous behavior and the viscosity of a drilling fluid under annular conditions. Hole cleaning and cuttings suspension capabilities are more accurately predicted by determining the viscoelastic properties of a drilling fluid rather than measuring viscosities at predetermined shear rates. To keep the hole clean when the annular mud velocity is limited by pump volume or enlarged hole section, the mud is viscosified to reduce the slip velocity of the formation cuttings.

William and Bruce (1951) recognized the importance of the velocity distribution in bore hole cleaning. Walker and Mayes (1975) considered the velocity distribution as a function of the mud properties. In general, an increase in the ratio of yield point, (YP) to plastic viscosity, (PV) or a decrease of the line slope, n (otherwise known as Power law index factor), results in a flattening of the velocity profile for the power law behavior of fluids.

Hopkin (1967) presented his analysis of the factors that affect cuttings removal. He related the slip velocity to the funnel viscosity and yield stress. He observed a 5% maximum safe concentration of particles in several drilling fluid types at which hole problems can be avoided. He concluded that increasing the mud density, inducing laminar flow in the annulus, and rotating drill pipe, all help to improve hole cleaning.

Sifferman et al (1974) investigated drill cuttings transport using full-scale vertical annuli under steady state condition. They used three different annular sizes and three types of fluids *(water, oil and Bentonitic mud)*. They studied the effects of major drilling parameters on the cuttings ratio and concluded that annular fluid velocity and their rheological properties had major effects on transport ratio while cutting size and fluid density had moderate effects. They further demonstrated that rotary speed, penetration rate, annular size and drill string eccentricity had minor effect on cutting transport ratio in vertical annulus.

Hussaini and Azar (1983) conducted an experimental study of drilled cuttings transport using conventional water base drilling fluids. They examined the relationship of yield point and plastic viscosity in terms of mud carrying capacity. In conclusion, they reported that fluid annular velocity plays an important role in the carrying capacity of drilling mud. However, the study did not incorporate the mechanism of the pressure loss at the bit and the circulating pressure loss.

Bizanti and Robinson (1988) used the transport ratio of solid density to fluid viscosity in examining the hole cleaning efficiency. An improvement in transport ratio with increase in fluid plastic viscosity was reported.

Belavadi and Chukwu (1994) presented an experimental study to evaluate cuttings transport parameters. The results of their study showed that the ratio of the density differences between the cuttings to the fluid viscosity has a significant effect on the transport ratio. The removal of small size cutting particles is greatly enhanced with pipe rotation when drilling with high-density mud circulated at high flow rates.

Wright, Chukwu, Khataniar and Patil (2003) studied the efficiency and cost effectiveness of hole cleaning using Hydraulic Horsepower and Jet Impact Force with the objective of maximizing the available hydraulics. The study showed that optimum hydraulic programs can be designed on the basis of minimum cost. Also Jet Impact Force can be optimized more cost effectively than the Hydraulic Horsepower at a flow exponent, m (function of drilling fluid properties) greater than 1.8. At m less than 1.6, the cost to optimize for Jet Impact Force and Hydraulic Horse power are equal.

Rheological Models

Fluids in general can be classified as Newtonian or non-Newtonian, based on their shear stress (τ) and shear rate (γ) relationship otherwise known as *"flow curve"* or *"rheogram"*. Newtonian fluids are those fluids that conform to a direct proportionality between the shear stress and shear rate at a given temperature and pressure. Non-Newtonian fluids are those fluids that do not conform to direct proportionality between shear stress and shear rate. No single equation has been proved to describe exactly the rheogram of all such fluids.

Rheological models are used to describe the shear stress versus shear rate relationship of viscous fluids. These models help predict fluid behavior across a wide range of shear rates. These models can be used to calculate the viscosity of the fluid but more importantly they are applied in this study for the determination of pressure losses and transportation efficiency of fluids for hole cleaning.

Most drilling fluids are non-Newtonian, and the most common rheological models that are used to characterize them are:

1. Bingham plastic fluid model, and
2. Power law fluid model

Bingham Plastic Fluid Model

Bingham plastic fluid model is one of the earliest fluid models used for describing and characterizing drilling fluids. The model is characterized by a linear shear stress-shear rate plot, which does not pass through the origin (**Figure 1**). A finite stress known as yield stress must be applied and once exceeded, the stress increases linearly with increasing shear rate. The slope of the curve drawn is called the plastic viscosity.

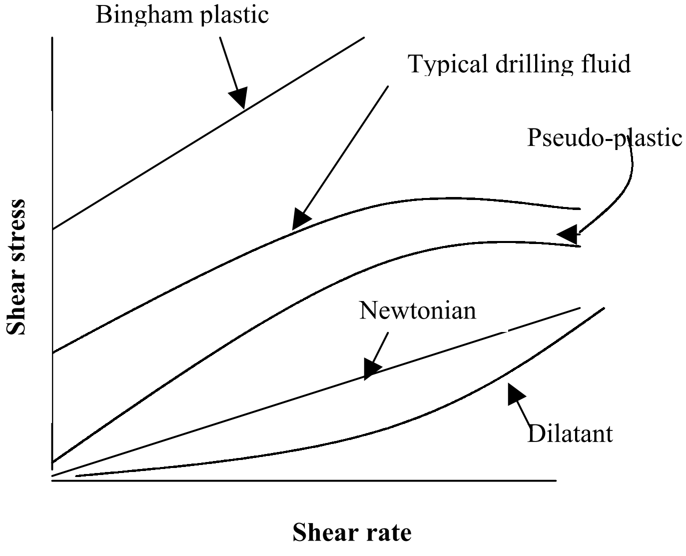

Figure 1: Different Fluid Rheograms

The constitutive equation for Bingham plastic fluid model is presented as:

$$\tau = \tau_o + \gamma\mu_p \qquad (1)$$

where;
τ_o is initial shear stress to initiate flow otherwise known as yield point,
γ is the shear rate, and
μ_p is the plastic viscosity.

Power Law Model

The Bingham Plastic Model exaggerates the shear stress of many drilling fluids at low shear rates. Many drilling fluids, particularly polymer-based fluids are better characterized by the Power Law Model.

In many cases, the power law fluid model more closely approximates actual fluid properties even when calculated from viscometer data. Though this model can be applied using data from annular shear rate ranges, it will provide much greater accuracy in predicting the performance of a drilling fluid in the annulus. This is especially true for the low-solids, highly shear-thinning fluid systems being used in the past.

This model describes the rheological behavior of the drilling fluids that do not exhibit yield stress *(i.e. yield stress is equal to zero).* The power law model has two parameters used to describe the flow, namely; n, the power law flow behavior index factor, and k, the consistency index factor which is synonymous to the viscosity of Newtonian fluid. The Power law exponent n, which is dimensionless, describes the departure of the fluid from Newtonian behavior. If n = 1.0, the fluid is defined as Newtonian. For n < 1, the fluid is characterized as pseudo-plastic power law fluid. For n > 1, the fluid is characterized as dilantant power law fluid. The fluid becomes more shear thinning as the value of n decreases from unity. The rheogram of these fluid classification is shown in Figure 1.

High values of the consistency factor,k may indicate a high viscosity, and fluids with such viscosity under near-zero shear rate conditions offer significant improvements in hole cleaning efficiency.

The constitutive equation representing power law fluids is given by equation (2).

$$\tau = k\gamma^n \qquad (2)$$

Data Collection and Analysis

Several authors in the past, (Aswad and Saleh (1967), Sifferman (1974), Lim and Chukwu (1996), Sample and Bourgoyne (1977), Sutko and Myers (1971), Belavadi and Chukwu (1994)), have used different factors and/or approaches to evaluate effective hole cleaning through lifting capacity of drilling fluid.

The fluid properties of two different drilling fluid systems were collected and used for the comparative evaluation of hole cleaning using the Bingham plastic and Power law fluids' models. Equations developed by previous investigations Moore, 1974, Chien,1972) were used to determine velocity profile, pressure drop, equivalent circulating density (ECD), slip velocity and cuttings transport efficiency using the two rheological fluid models considered in this study.

Hole Cleaning Parameters

The particle Slip Velocity, V_s, is an important factor in the lifting capacity of drilling fluid, which aids hole cleaning. It is defined as the velocity at which a particle tends to settle in a fluid due to its own weight. Also it depends on the particle size, its geometry, specific weight and the fluid rheological properties. Particle slip velocity correlations have been developed over the years in order to prevent slippage of drill cuttings around drill collars and around the drill bit, which in turn lead to regrinding of these cuttings causing a waste of the limited energy available to the drill bit.

Particle slip velocity, V_s can be estimated using equation (3).

$$V_s = A \times \sqrt{B \times C} \qquad (3)$$

Where:

$$A = 12.0*(\mu_{eff}/d*\rho_f) \qquad (3a)$$

$$B = 1+(7.27*d*(\rho_p-1)/\rho_f) \qquad (3b)$$

$$C = ((d*\rho_f)/\mu_{eff})^2-1 \qquad (3c)$$

And; ρ_f is the fluid density
ρ_p is the particle density
d is the particle diameter.

The effective fluid viscosity, (μ_{eff}) for the Bingham plastic and Power law fluids' models was obtained from equations (4) and (5), respectively.

$$\mu_{eff} = (\tau/\gamma) + \mu_p \qquad (4)$$

and

$$\mu_{eff} = k(\gamma)^{n-1} \qquad (5)$$

The cuttings transport efficiency (TE) was calculated using equation (6).

$$TE\,(\%) = ((V_a - V_s)/V_a) * 100 \qquad (6)$$

Using appropriate hydraulic equations and relationships, or equation (7) below, the maximum rate of penetration (MaxROP) was determined for the two rheological models and fluids at assumed cuttings concentration (Ca) of 5% (which represents efficient hole cleaning).

$$MaxROP = \frac{4QR_TCa}{\Pi d^2_b} \qquad (7)$$

Where tansport ratio (R_T) was obtained from equation (8).

$$R_T = 1 - (v_s/v_a) \qquad (8)$$

And: v_a is the average fluid velocity.
Q is the fluid flow rate
D_b is the equivalent bit nozlle diameter

Also, using appropriate annular pressure loss equations for rheological models for each of the fluids (Moore, 1974), the Equivalent circulating density (ECD) was obtained using equation (9).

$$ECD = \rho_o + \frac{\sum \Delta P_a}{0.052\ D} \qquad (9)$$

where: ρ_o is the original mud density
ΔP_a is annular frictional pressure loss
D is total hole depth drilled

Table 1 shows the calculated results.

Table 1: Calculated Hole Cleaning Parameters.

	Bingham Plastic Fluid Model		**Power law fluid Model**	
	Fluid A	*Fluid B*	*Fluid A*	*Fluid B*
Transport Efficiency, TE, (%)	94.62	81.18	99.91	99.23
MaxROP, (ft/sec)	2.425	0.895	2.561	1.094
ECD(ppg)	7.63	11.20	12.13	9.85

ECONOMIC EVALUATION AND ANALYSIS

Horsepower Requirements

The hydraulic horsepower is the rate of work done by a fluid at a given pressure. It is due to the significant importance of mud pump horse power that a good understanding of the rig's consuming power components and it's analytical evaluation of the optumum use of available power is essential.

When the hydraulic horsepower is insufficient, the bit regrinds cutting in the hole bottom instead of transporting them to the surface, thus comsuming the bit life and reducing the rate of penetration. This will inversely increase the drilling cost. Wasteful regrinding of cuttings is prevented if the fluid cirulated through the bit removes the cuttings as rapily as they are generated.

The hydraulic horsepower (HHP) can be determined for each of the fluids using equation (10).

$$HHP = (q_{opt} \Delta P_{Copt})/1714 \qquad (10)$$

Where: q_{opt}, ΔP_{Copt} are the optimum flow rate and optimum circulating friction pressure loss, reepectively, and are determined from the methods of Wright, et al (2003).

The total cost per foot (C_t) equation for maintenance and fuel is given by Wright, et al, (2003) as;

$$C_t = 0.350\ HHP + 10.96\{1.143 HHP/q_{opt}\}^{1.52} \qquad (11)$$

Equation (11) was used in this study to determine the operating cost for each of the drilling fluids for the two rheological models considered.

Table 2 shows the calculated results for each fluid from the two rheological models.

Table 2: Calculated results of the operating Cost.

	Bingham Plastic Fluid Model		**Power Law Fluid Model**	
	Fluid A	**Fluid B**	**Fluid A**	**Fluid B**
HHP (hp)	10.26	12.22	10.25	11.78
C_t (\$/ft)	16.42	16.48	14.93	15.14

Conclusions

1. The properties of drilling fluids A and B were used to determine the Transport Efficiency (TE), Maximum Rate of Penetration (MaxROP), and Equivalent Circulating density (ECD) from both the Bingham plastic and Power law rheological models. Comparative results show that the Power law model is more efficient model for evaluating hole cleaning.

2. An economic evaluation of the hydraulics from the energy and horse power requirements for both rheological models showed that the Power law fluid model provided a better transport efficiency, and hence more economical in terms of minimum drilling cost.

3. The data of table 2 show that lesshydraulic horsepower is required to lift cuttings from a drilled hole using power law fluids. Hence, energy savings of between 9-10% can be achieved over Bingham plastic fluids using Power law fluids to maintain efficient hole cleaning.

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