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Selection of dilling mds uing wll hdraulic clculations

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ABSTRACT

One of the most important factors which affects mud selecting is the rheology conditions of mud, which has the role of controlling the well hydrodynamic behaviors such as pressure drops through the string pipes, bit, annulus, upraised mud pressure (UMP) and cuttings movement from the depth. In this study a computer program has been prepared to calculate the density and viscosity (or rheological index) of mud. This program has been developed based on the pressure drop equations and the settling velocity equation of the cuttings for Bingham and power law fluids in a reverse procedure to find density and viscosity of drilling mud. A combined algorithm has been prepared to solve these strongly bad behavior equations. The results have been compared with the assumed values in direct hydraulic calculations and a maximum error of 0.14% has been observed.

KEYWORDS

Drilling mud selection;
Hydraulic calculations;
Bingham fluid;
Power law fuid.

1. INTRODUCTION

Selection of the proper drilling fluid is important to the success of a drilling operation. No fluid is suitable for all situations. Fluids with different base liquids, different dominating cations in the aqueous phase, different chemical additives, or broadly diverse physical characteristics have different behaviours, making for a large menu of choice[1]. Fluids for drilling operations are classified into five major fluid types based primarily equivalent circulating density (gas, mist, foam, gasified liquid and liquid). Further delineation within these groups is dependent upon considerations based on well flow characteristics, well fluid type, surface operating pressure, fluid containment, well control, and applicable health, safety, and environmental issues.

Final fluid selection for drilling operations can be extremely complex. Key issues such as reservoir characteristics, geophysical characteristics, well fluid characteristics, well geometry, compatibility of drilling fluids and reservoir brines, hole cleaning, temperature stability, corrosion, data transmission, surface fluid handling and separation, formation lithology, filtration, health and safety, environmental impact, fluid source availability, as well as the primary objective for drilling all have to be taken into consideration before final fluid design[2]. However, the drilling fluid selection is to somehow due to drilling project manager experience and there is no systematic procedure for doing so in the literature.

Havenaar[3] extended the works of Beck et al.[4] as well as Bingham[5] to characterize the plastic (Bingham) fluid flow hydrodynamics in pipes and bit nuzzle.

Melrose et al.[6] presented a simplified solution to the problem of computing the pressure drop for the flow of drilling mud in the annulus of the wellbore. Koch[7] presented the first pocket calculator to select the proper nozzle and pump liner size. Jeu et al.[8] emphasized the effect of proper fluid selection on controlling skin in deepwater drilling. Many other researchers introduce several methods to select proper mud[9,10].

In this study, based on hydraulic calculations a new method for selecting drilling mud is introduced. This method takes into account pressure drop and settling velocity equations to find optimized density and viscosity for a drilling operation.

2. Theory

One of the most important roles of circulating mud in rotary drilling operation is cleaning the hole in which the cutting particles with density ρ_s must be transported from the down hole to the surface. Bourgoyne et al.[11] have presented the following formula for particle settling velocity in static mud:

$$v_{sl} = \frac{82.87 d_s^2}{\mu_a}(\rho_s - \rho_m) \qquad N_{Re} < 3 \tag{1}$$

$$v_{sl} = \frac{2.9 d_s (\rho_s - \rho_m)^{0.667}}{\rho_m^{0.333} \mu_a^{0.333}} \qquad 3 < N_{Re} < 300 \tag{2}$$

$$v_{sl} = 1.54 \sqrt{d_s \frac{(\rho_s - \rho_m)}{\rho_m}} \qquad N_{Re} > 300 \tag{3}$$

In which μ_a represents the apparent viscosity of the mud and can be calculated for both plastic (Bingham) and Power-law fluids, and can be calculated as follows:

$$\mu_a = \mu + \frac{91.44 Y_b d_s}{v_{ann}} \qquad \text{(plastic fluids)} \tag{4}$$

$$\mu_a = 332.64K\left(18.29\frac{D_h - D_o}{v_{ann}}\right)^{1-n}\left(\frac{2+\frac{1}{n}}{0.0208}\right)^{n} \qquad \text{(Power – lawfluids)} \tag{5}$$

and the Reynolds number is defined as:

$$N_{Re} = \frac{423 \rho_m v_{sl} d_s}{\mu_a}$$

In practice the annular mud velocity must be higher than the particles settling velocity to keep the hole clean. The mud velocity in the annulus depends on pump power and string size and independent of mud properties. Thus knowing the pump flow rate and strings dimensions one can define transport ratio in the hole, as follows[12]:

$$TR = 1 - \frac{v_{sl}}{v_{ann}} \tag{6}$$

Equations 1 through 6 (named as the first set of equations) make a set of equations which drilling mud rheological properties (such as density, viscosity/ rheological index and …) must satisfy them. Equation 6 is the key step in the first set of equations. Once a value assumed between zero and one for transport ratio, the settling velocity can be found and then it must be compared with the calculated one, as will be shown next.

The second equation arises from the principle of the conservation of energy. When this equation is applied to the case of circulating drilling mud, as in drilling a well, where the mud is pumped out of the mud pit and circulated back into the pit, the following equation (Bernoulli equation) may be obtained[15]:

$$\text{Hydraulic horsepower(Pump pressure)} = \text{Sumof flowing pressureloss} \tag{7}$$

or

$$\text{Upraised Mud Pressure (UMP)} = \text{Pump Pressure} - \Delta P_{SE} - \Delta P_{Str} - \Delta P_{Bit} - \Delta P_{Ann} \tag{8}$$

where ΔP_{SE}, ΔP_{Str}, ΔP_{Bit} and ΔP_{Ann} denotes pressure drop through surface equipments, strings, bit and annulus respectively. These values arise by considering momentum equation (Navier-Stokes equation) in each zone of the well[11,13]. The set of Bingham(plastic) and power law equations for pressure drop through the well (ΔP_{SE}, ΔP_{Str}, ΔP_{Bit} and ΔP_{Ann}) are presented in TABLES 1 and 2 respectively[14].

The UMP must be some value greater than the surface (mud pit) pressure (about 101.3 kPa). However the economic considerations limit the value around the mud pit conditions. Thus having a set of two equation (one for settling velocity and the other for UMP) one must calculate the density and viscosity of the mud.

3. Numerical solution

To solve the mentioned equations a computer program is prepared and several famous and well understood numerical algorithms were tested. But unfortunately none of them led to the correct answer. The discontinuous behavior of the pressure drop equations and non linearity of the settling velocity equations were the main causes.

Finally, by discretizing viscosity in μ direction and

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TABLE 1: Pressure drops for plastic drilling fluids ($\tau = Y_b + \mu\dot{\gamma}$)[14]

	Pressure drops	Critical velocity
Strings	$\Delta P_{str} = \dfrac{LQ\mu}{612.95 D_i} + \dfrac{LY_b}{13.26 D_i} \quad V_{str} < V_c^{str}$ $\Delta P_{str} = \dfrac{L\rho_m^{0.8} Q^{1.8}\mu^{0.2}}{901.63 D_i^{4.8}} \quad V_{str} > V_c^{str}$	$V_c^{str} = \dfrac{2.48}{D_i \rho_m} \times \left(\mu + \sqrt{\mu^2 + 73.57 Y_b D_i^2 \rho_m}\right)$
Bit	$\Delta P_{nuzzle} = \dfrac{\rho_m Q^2}{2959.41 C^2 A_{nuzzle}^2}$	——
Annulus	$\Delta P_{ann} = \dfrac{LQ\mu}{612.95(D_h + D_o)(D_h - D_o)^3} + \dfrac{LY_b}{13.26(D_h - D_o)} \quad V_{ann} < V_c^{ann}$ $\Delta P_{ann} = \dfrac{L\rho_m^{0.8} Q^{1.8}\mu^{0.2}}{901.63(D_h + D_o)^{1.8}(D_h - D_o)^3} \quad V_{ann} > V_c^{ann}$	$V_c^{ann} = \dfrac{3.04}{(D_o - D_i)\rho_m} \times \left(\mu + \sqrt{\mu^2 + 40.08 Y_b (D_o - D_i)^2 \rho_m}\right)$

TABLE 2: Pressure drops for power-law drilling fluids ($\tau = K|\dot{\gamma}|^{n-1}\dot{\gamma}$)[14]

Pressure drops	Critical Velocity
$\Delta P_{str} = \dfrac{KL}{13.26 D_i}\left[\dfrac{2.59Q}{D_i^3}\dfrac{(3n+1)}{n}\right]^n \quad V^{str} < V_c^{str}$ $\Delta P_{str} = \dfrac{(\log n + 2.5)\rho_m Q^2 L}{58.94 D_i^5} \times \left[\dfrac{D_i^4 K\left(\dfrac{2.59Q}{D_i^3}\dfrac{(3n+1)}{n}\right)^n}{18.07 Q^2 \rho}\right]^{\frac{14+\log n}{2}} \quad V^{str} > V_c^{str}$	$V_c^{str} = 0.6\left(\dfrac{(3470 - 1370n)K}{1.27\rho}\right)^{\frac{1}{2-n}} \times \left(\dfrac{3n+1}{1.25 D_i n}\right)^{\frac{n}{2-n}}$
$\Delta P_{nuzzle} = \dfrac{\rho_m Q^2}{2959.41 C^2 A_{nuzzle}^2}$	——
$\Delta P_{ann} = \dfrac{KL}{13.26(D_h - D_i)} \times \left[\dfrac{5.18Q}{(D_h + D_o)(D_h - D_o)^2}\dfrac{(2n+1)}{n}\right]^n \quad V^{ann} < V_c^{ann}$ $\Delta P_{ann} = \dfrac{(\log n + 2.5)\rho_m Q^2 L}{58.94(D_h + D_o)^2(D_h - D_o)^3 D_i^5} \times \left\{\dfrac{(D_h + D_o)^2(D_h - D_o)^2 K}{22.13 Q^2 \rho} \times \left(\dfrac{5.18Q}{(D_h + D_o)(D_h - D_o)^2}\dfrac{(2n+1)}{n}\right)^n\right\}^{\frac{14+\log n}{2}} \quad V^{ann} > V_c^{ann}$	$V_c^{ann} = 0.6\left(\dfrac{(3470 - 1370n)K}{2.05\rho}\right)^{\frac{1}{2-n}} \times \left(\dfrac{2n+1}{0.64(D_h - D_o)n}\right)^{\frac{n}{2-n}}$

using false-positioned method[16] to find density, ρ_m, from settling velocity equations (Eqs. 1-6) and checking the results with pressure drop equations (Eq. 8), one can solve the problem. Figure 1 shows the details of the algorithm.

To show the problem more clear, the following two examples are considered.

Example 1

This example is a direct hydraulic calculation. The viscosity and density of the mud are known and the transport ratio, the total pressure drop through the well and upraised mud pressure are calculated. The input and output are shown in TABLES 3 and 4 respectively.

TABLE 3: Input parameters for example 1

Type	Length(ft)	ID(inch)	OD(inch)
Drill pipe	6986.4	4.28	5
Drill collar	557.6	2.85	6.75
Casing	7543	-	8.5

Density= 9.59 lb_m /gal,viscosity= 22 c.p, pump flow rate= 369 gal/min, Pump pressure= 2150 psi, Cuttings density= 45.87 lb_m /gal, Cuttings diameter= .25 inch, Mud type= water base, Fluid type= Bingham

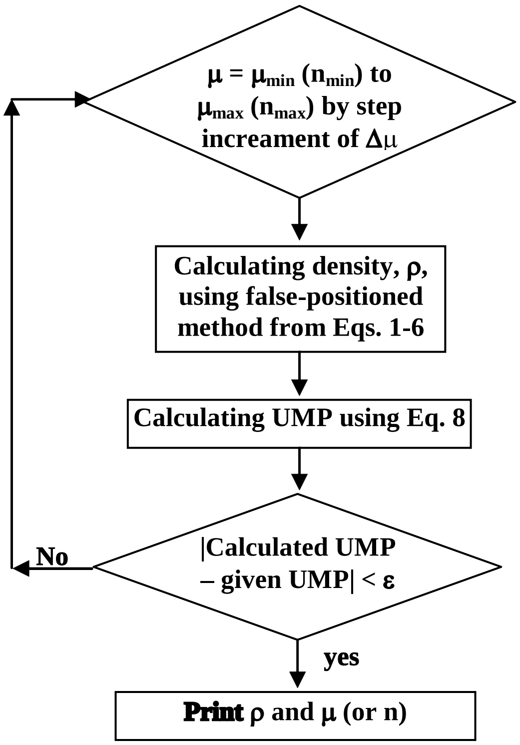

Figure 1: Schematic of combined algorithm

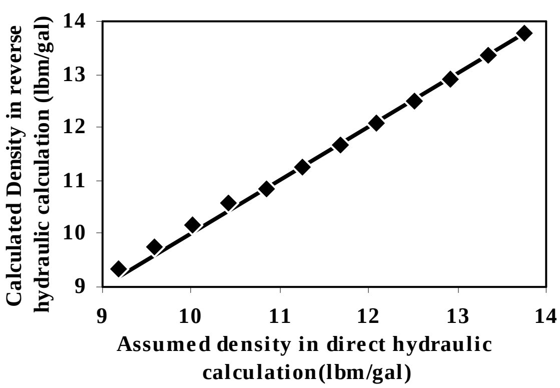

Figure 2: The comparison of assumed and calculated density in direct and reverse hydraulic calculations $\mu = 45$ c.p

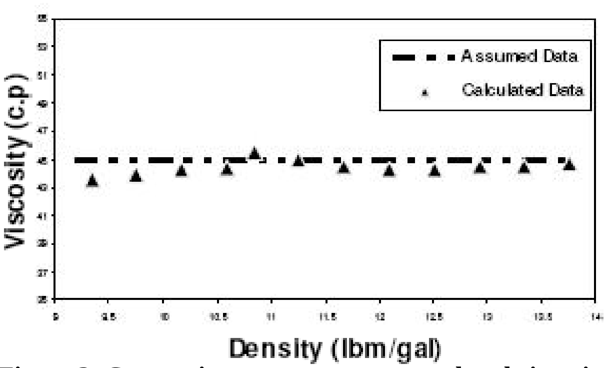

Figure 3: Comparison assumed and calculated viscosity and density in direct and reverse hydraulic calculations for μ= 45 c.p

TABLE 4: Output for example 1

Type	Pressure drop (psi)
Drill strings (pipe &collar)	552
Bit	1395
Annulus	177.34
Total	2124.34
Upraised mud pressure	25.66

Settling velocity= 1.4 ft/sec, Transport ratio= 0.73

TABLE 5: Input parameters for example 2

Type	Length(ft)	ID(inch)	OD(inch)
Drill pipe	6986.4	4.28	5
Drill collar	557.6	2.85	6.75
Casing	7543	-	8.5

Transport ratio= 0.73, Upraised mud pressure= 14.7 psig, Pump flow rate=396 gal/min, Pump pressure= 2150 psi, Cuttings density= 45.87lb_m /gal, Cuttings diameter= .25 inch, Mud type= water base, Fluid type= Bingham

TABLE 6: Output for example 2

Viscosity (c.p)	Density (lb_m/gal)	Settling velocity (ft/min)	Mud velocity in annulus (ft/min)
21.98	9.58	1.28	4.77

Example 2

Example 2 is a reverse hydraulic calculations. The transport ratio and upraised mud pressure are known and the viscosity and density of the mud are calculated. This example shows the selection of drilling fluid using well hydraulic calculations. The input and output are shown in TABLES 5 and 6 respectively.

4. RESULTS

4.1. Accuracy

To show the accuracy of the method, we used several densities in a constant viscosity to compute the transport ratio and pressure drop as well as UMP such as example 1. Then using these transport ratios and upraised mud pressures, we calculated the densities and viscosities from the combined method as shown in example 2.

Figure 2 shows calculated density from reverse hydraulic calculations versus assumed density in direct method for a constant viscosity of 45 c.p. It can be seen that there is excellent agreement between the calculated results and assumed values. In figure 3 the calculated viscosity and density from reverse hydraulic calculations are compared with assumed values in direct method for μ=45 c.p. To observe the maximum error in calculations, one may define the square relative

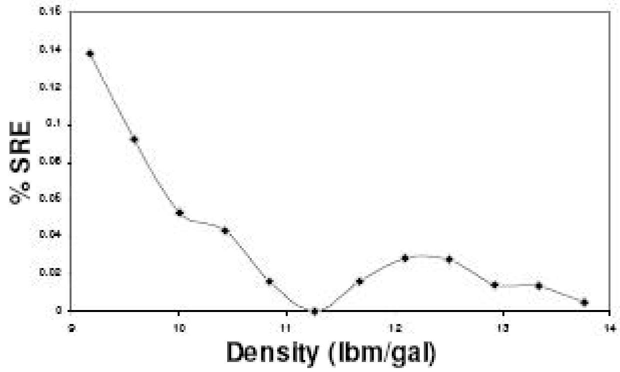

Figure 4: Square relative error versus density for μ= 45 c.p.

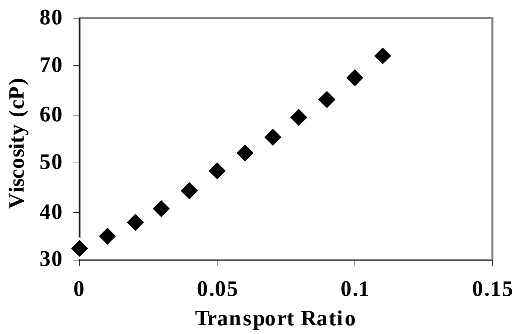

Figure 5: Effect of transport ratio on calculated viscosity for UMP=constant

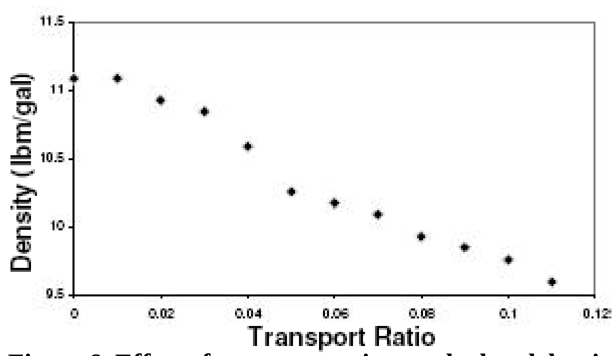

Figure 6: Effect of transport ratio on calculated density for UMP= constant.

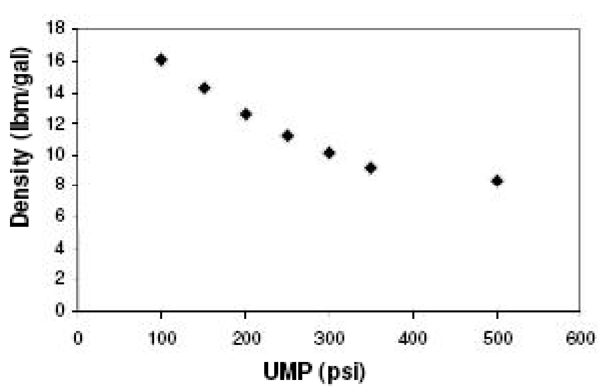

Figure 7: Density versus UMP for transport= constant

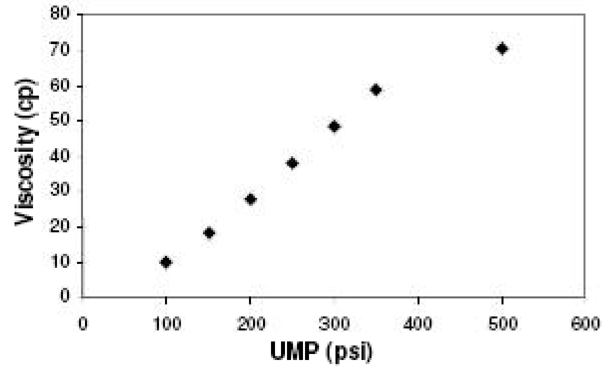

Figure 8: Density versus UMP for transport ratio = constant

error (SRE) as follows:

$$\mathrm{SRE} = \left[\frac{\left(\mu^{\mathrm{assumed}} - \mu^{\mathrm{calculated}}\right)^2}{\left(\mu^{\mathrm{assumed}}\right)^2} + \frac{\left(\rho^{\mathrm{assumed}} - \rho^{\mathrm{calculated}}\right)^2}{\left(\rho^{\mathrm{assumed}}\right)^2} \right] \times 100 \quad (8)$$

The SRE versus density is shown in figure 4 and a maximum error of 0.14% is observed which is acceptable for such non linear equations.

4.2. The effect of parameters

After confirming the mathematical model, the effect of transport ratio and UMP on fluid rheological parameters is studied. Figures 5 and 6 show the effect of transport ratio on mud viscosity and density respectively for UMP of a constant value. Increasing the transport ratio decreases the cuttings settling velocity (see Eq. 6) and Eqs 1 through 3 predicts increasing viscosity and decreasing density. This opposite behavior of viscosity and density sets a constant value for UMP. It must be noted that no data points yield over the shown domain and even between two neighbor points, which means that the results of above calculations are broken off. It may be the result of discontinuity of pressure drop equations and also the behavior of false-positioned method.

Figures 7 and 8 show the effect of desirable UMP on mud rheology parameters when transport ratio is constant. As shown in figure 7 the density decreases as UMP increases. However, the opposite behavior is observed for the viscosity (see figure 8). These effects can be explained by considering Equation 8 as well as Eqs. in TABLES 1 and 2. As the density decreases, the pressure loss decreases. This causes to increase UMP. For fixing transport ratio, when density decreases, the viscosity must increase.

Nomenclature

A- Area (in^2); C- Nuzzle coefficient; D_{h-}Hole diameter (in); D_o - Strings outside diameter (in); D_i - Strings inner diameter (in); d_s - Cuttings diameter (in); K- Consistency index (lb.s^n/ (100ft^2)); L - Strings length (ft); n - rheological index; P - Pressure (psi); Q- Pump flow rate (gal/min); v- Velocity (ft/sec); Y_b - Yield point (lbm/ (100ft^2))

Greek letters

Δ- Pressure drop (psi); ρ - Density (lbm/gal); μ - Viscosity (c.p); γ- Share rate (sec/ft); τ - Share stress (lbm/ (100ft^2))

Superscripts

a- apparent; ann – annulus ; Bit- bit; sl – settling ; str- string

Subscripts

c- critical; m- mud; nuzzle- nuzzle; s- cuttings

5. CONCLUSIONS

In this study a computer program for selecting drilling mud based on hydraulic calculations is introduced. This software will be able to do direct and reverse well hydraulic calculations. In the direct calculations, by specifying equipment sizes, viscosity and density of the mud, the pressure drop through the well and upraised mud pressure are calculated. In the reverse calculations, a new approach for calculating density and viscosity/rheological index of a drilling mud by specifying transport ratio and UMP is introduced. Also, this software takes into account dynamic filtration in the well. Detailed of this filtration will be given in the future work.

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