Effect of Non-Newtonian Behavior of Fluids in the Re-Suspension of a Drilled Cuttings Bed

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ABSTRACT

This paper presents a discussion on the role of the rheological properties of a drilling fluid in the erosion of a solids bed formed in the bottom of a horizontal annulus. A series of experimental tests conducted on a large scale flow loop with 3 different polymer solutions was used as data base for fitting a mechanistic model to predict critical shear stresses at the interface fluid – solids bed. A mechanism of normal stress response is proposed to explain the different performances of Carboxy Methyl Cellulose, Xhantam Gum and Partially Hydrolyzed Polyacrilamide Solutions.

INTRODUCTION

Solids transport is a major issue in high angle oilwell drilling design. Excessive accumulation of drilled cuttings in the annular region formed by the well walls and the drillstring may lead to serious and costly problems for the drilling operation. Fig. 1 illustrates the formation of a cuttings bed in the lower portion of a horizontal annulus.

A lot of experimental and theoretical effort have been spent, in the last 2 decades, in the modeling of the involved phenomena[1-6].

Drilling fluids are non-Newtonian type solutions/suspensions, which rheological properties are measured, in the field, by simple concentric cylinder rheometer tests. These properties serve as input data for computer simulators, which have been developed and used successfully as design and troubleshooting tools while drilling in high angle.

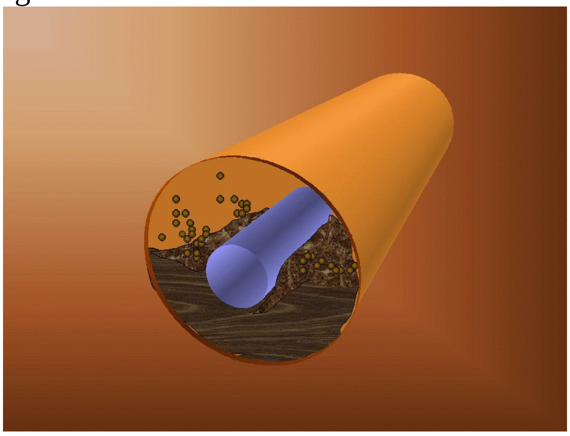

Figure 1 – Cuttings Bed Formation in Horizontal Annulus

With the time, drilling fluid composition evolved from clay type suspensions to solids free polymeric solutions. At this point, different composition fluids which have similar field rheological properties behave differently concerning the capacity of eroding a cuttings bed deposited on a horizontal annulus. Martins et al[6] details an extensive experimental effort spent in the determination of interfacial stresses on a stratified solid liquid annular flow. At that time, all experiments were based on one type of fluid (Xhantam Gum solutions) and correlation development was purely empirical.

The present study involved both theoretical and experimental approaches. Initially, a detailed rheological characterization of 3 different types of polymers was performed. The same fluids were then tested, on a large-scale flow loop, for bed erosion capacity. The next step was the prediction, using a numerical flow simulator, of critical shear stresses in the interface fluid-bed. Finally, a mechanistically based correlation between critical shear stresses for bed erosion and major influent rheological parameters was obtained.

EXPERIMENTAL PROGRAM

Experiments have been conducted on a pilot scale flow loop. The test section consists of a 12m long 0.127 m diameter acrylic pipe where 0.0508m and 0.0635 m PVC internal pipes are introduced to represent two typical annular geometries of horizontal wells. A solids injection system is coupled at the entrance of the test section. The tests consisted of the following steps:

- Build up of a constant height solids bed along the test section;
- Interruption of the solids injection and increase of the fluid flow rate: the bed is eroded until a new equilibrium height is obtained;
- Measurement and recording of the pressure drop and bed perimeter.

Experimental data have been obtained for different annular geometries, and different values of solid/fluid properties and operational variables. Hence, variables such as eccentricity, rheology, fluid and flow rate have been changed. The mass flow rate of the polymeric solution has been measured by a Coriolis type equipment, while pressure drop has been determined by a differential pressure transducer. The sands bed perimeter has been recorded by direct length measurements.

TEST MATRIX

A total of 16 different tests were performed using solutions of different polymers at different concentrations, to represent the drilling fluids and particles of sandstone of different diameters. These tests resulted in around 220 experimental pairs relating flow rates ad bed heights for a given test condition.

The following parameters have been changed:

- Types of polymer: Xhantan Gum (XC), Partially hydrolyzed polyacrilamide (PHPA) and Carboxy Methyl Cellulose (CMC)
- Annular diameter ratio: 0.408
- Annular eccentricity: 0 (concentric) and 1 (fully eccentric)
- Fluid rheology: low, average and high viscosity (details in the next section)
- Solids diameter: 0.234 in.

EXPERIMENTAL RESULTS

a) Rheological Behavior

Each polymeric solution was prepared in three different concentrations resulting in the fluids named low, average and high viscosity. The concentrations are defined in a way that all the 3 low (or average or high) viscosity fluids have similar behavior when tested at high shear rates in a rotational rheometer[7]. Table 1 shows the adjusted rheological parameters for the Ostwald de Waele and Herschell Bulkley models based on the concentric cylinder data.

Table 1 - Rheological parameters

Fluid	**Viscosity**	**Power Law**		**Herschel-Bulkley**		
		K(kgf s^n/m2)	n	K(kgf s^n/m2)	n	τ_o (kgf/m2)
PHPA	Low	0.00397	0.51	0.00397	0.51	0
PHPA	Average	0.0127	0.44	0.01042	0.46	0.0097
PHPA	High	0.09294	0.32	0.09294	0.32	0
XC	Low	0.00062	0.67	0.00062	0.67	0
XC	Average	0.0063	0.56	0.00352	0.63	0.0221
XC	High	0.0874	0.32	0.01421	0.53	0.2471
CMC	Low	0.00076	0.79	0.00058	0.82	0.00357
CMC	Average	0.00362	0.68	0.01042	0.72	0.00234
CMC	High	0.03945	0.46	0.03945	0.46	0

Results indicate that CMC fluids tend to adjust properly as power law fluids since they present very low yield stresses in the fitting of a Herschell-Bulkley model. On the other hand XC and PHPA fluids present much higher yield stresses than CMC fluids when fitted to Herschell-Bulkley model. The results obtained from the concentric cylinder rheometer will be used in further analysis due to its adequacy for field use. Zero values for yields stresses reflect problems in fitting the model.

Fig. 2 shows the results obtained for the first normal stress differences (N_1) of PHPA and XC solutions using a commercial cone and plate rheometer.

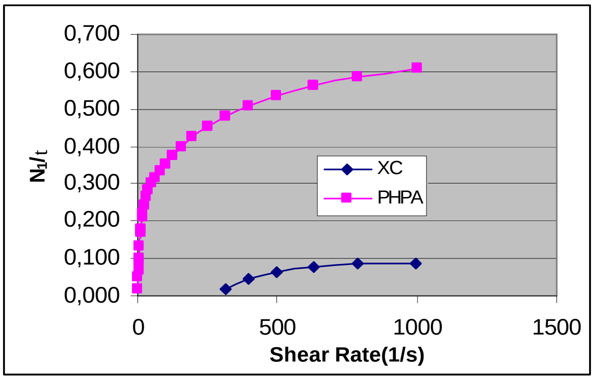

Figure 2 – N_1 evaluation

Results indicate positive values of N_1 for the PHPA solution submitted to shear rates greater than 3 s^{-1}. For the XC solution, on the other hand, positive values of N_1 were observed in shear rates greater than 1000 s^{-1}. No positive results could be measured for CMC solutions.

b) Cuttings Bed Erosion Capacity

Figs. 3, 4 and 5 show the effect of the type of fluid in the erosion capacity of a solids bed, considering a concentric annulus.

Results indicate that for the same "viscosity" (low, average or high) the CMC fluids tend to behave more efficiently than the XC and PHPA fluids. Similar results are obtained for the eccentric annulus (Figs. 6,7 and 8), with higher flow rate requirements when compared with the analogous concentric case.

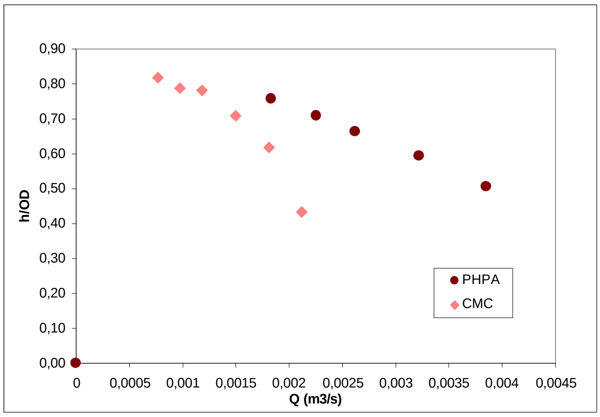

Figure 3- Bed Erosion With Low Viscosity Fluids – Concentric Annulus

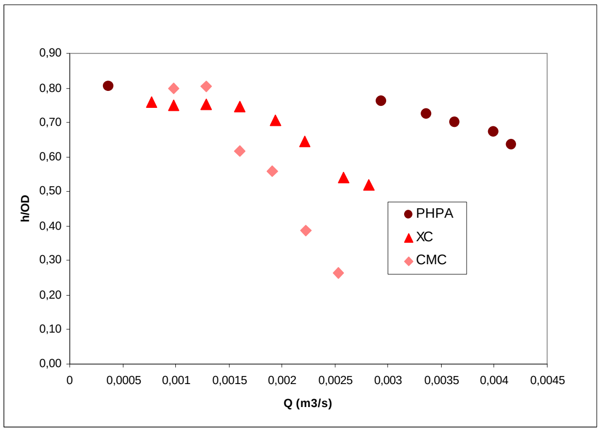

Figure 4- Bed Erosion With Average Viscosity Fluids – Concentric Annulus

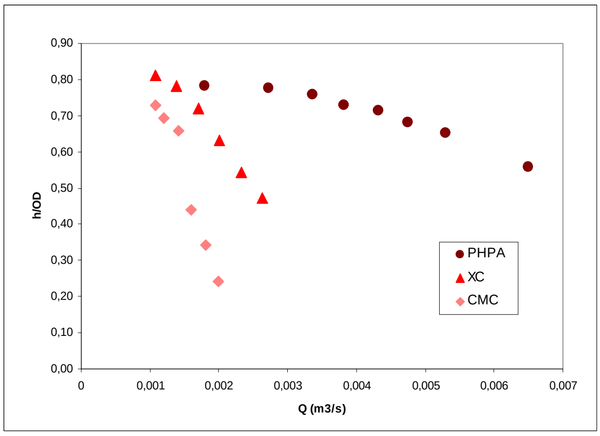

Figure 5- Bed Erosion With High Viscosity Fluids – Concentric Annulus

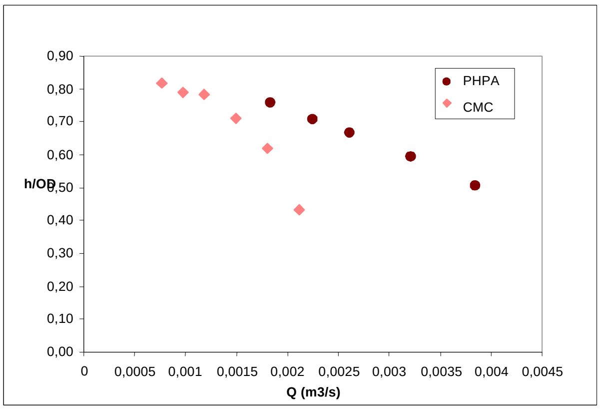

Figure 6- Bed Erosion With Low Viscosity Fluids – Eccentric Annulus

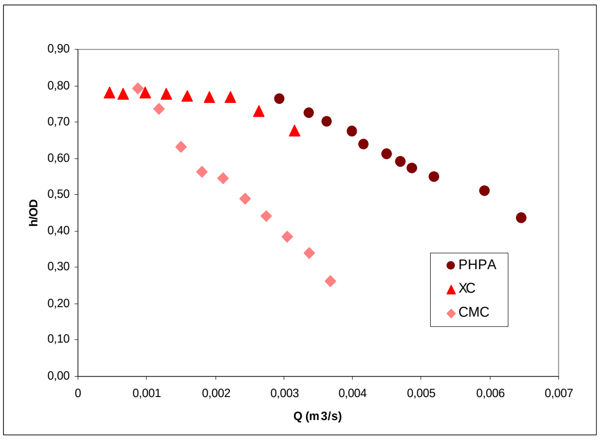

Figure 7 - Bed Erosion With Average Viscosity Fluids – Eccentric Annulus

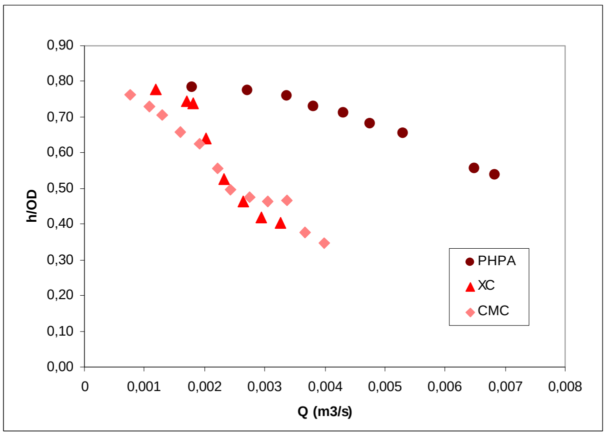

Figure 8 - Bed Erosion With High Viscosity Fluids – Eccentric Annulus

MODELING

The next step is the proposition of a model to predict the equilibrium bed height after an erosion process. The idea is to predict the shear stress required to put in movement a solid particle. A first effort, presented by Martins et al.[8], is based on the schematics shown in Fig. 6. The torque values of the several forces acting upon the top particle must add to zero, so that the top particle be at the imminence of moving. The main focus of the study is to analyze the effect of rheology on bed erosion capacity. The final correlation should be function of the rheological parameters, fluid and solids density and particle diameter. The development of this correlation is based on equations and theories presented in the literature. The fundamentals of stratified solid-liquid flows are detailed by Wilson[9] and Shook & Roco[10] . The idea is to develop a semi-empirical or mechanistic correlation by incorporating most of the physics taking place in the process, and finally use the experimental data to fit the final behavior.

The triangle formed by the three circumference centers is equilateral. This makes it to determine the levers of the several forces in relation to point P. The forces that act upon the top particle are the gravity force F_G and the buoyancy force F_E, and the hydrodynamic forces of drag and lift, F_D and F_L, respectively. Wicks, cited by Govier & Aziz[11], has presented an analysis about some aspects of solid-liquid flows in the presence of a cuttings bed. They reasoned through associating the lifting and rolling of the

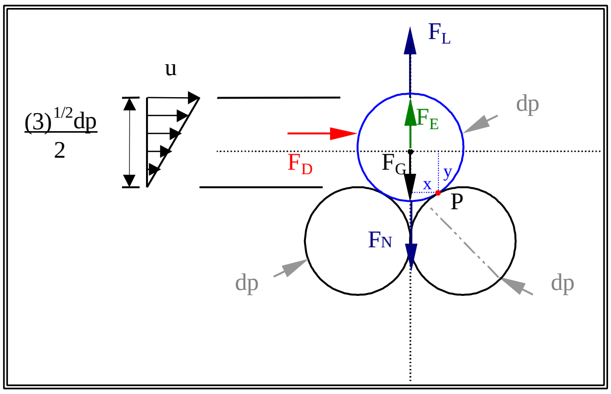

Figure 9 – Schematic showing the forces acting upon a particle in the imminence of moving

particles along the surface of the cuttings bed, and arrived the description of the forces acting upon the particle and established the condition for incipient motion as:

$$F_L x + F_D y + F_E x = F_G x \qquad (1)$$

where F_L is the lift force, F_D is the drag force, F_E is the buoyancy force, F_G is the gravity force, *y/x* is a shape factor. By substituting for the expressions of these forces in terms of the geometrical and flow parameters, one gets:

$$C_L a \frac{1}{2} r\, u^2 + \frac{y}{x} C_D a \frac{1}{2} r\, u^2 + v_s r\, g - v_s r_s\, g = 0 \qquad (2)$$

where C_L and C_D are the lift and drag coefficients, respectively, *a* is the average projected cross-sectional area of the particle ($=\pi d_p^2/4$), v_s is the average volume of the particle ($=\pi d_p^3/6$), *r* and r_s are the fluid and solids densities, respectively, and *g* is the acceleration o gravity.

Substituting for the expressions of *a* and *v*, using the C_L and C_D definitions by White[12] and Sá et al.[12] , respectively and adopting the Ostwald de Waele model, the Eq. 2 was rewritten, by the authors, as:

$$A\left(\frac{dp\, t_w^{\frac{1}{2}+\frac{1}{n}}}{\sqrt{r}\, K^{\frac{1}{n}}}\right) + \left\{\left[\left(B \frac{K^{\frac{2}{n}}}{r\, dp^2 t_w^{\frac{2}{n}-1}}\right)^{0,85} + 1.01\right]^{1,2} \cdot \frac{d_P{}^2 t_w{}^{\frac{2}{n}}}{K^{\frac{2}{n}}}\right\} - \frac{4}{3}\left(\frac{r_s}{r} - 1\right) g = 0 \qquad (3)$$

where A, and B are coefficients to be determined. Eq. 3 presents an implicit formulation for the determination of τ_w as a function of the rheological parameters of the fluid (*K* and *n*), of the fluid and solids densities (*r* and r_s) and of the particle diameter (d_p). The main limitation of that model was that different coefficients had to be obtained for different polymers, despite of the different Ostwald de Waele rheological parameter used.

The present proposition is that an additional term representing normal forces, due to the flow of viscoelastic fluids, would tend to compact the bed against the wall. This term is also highlighted in Fig. 6. In this case, Eqs. 1 and 3 would be rewritten as:

$$F_L x + F_D y + F_E x - F_N x = F_G x \qquad (4)$$

$$C_L a \frac{1}{2} r\, u^2 + \frac{y}{x} C_D a \frac{1}{2} r\, u^2 + v_s r\, g - v_s r_s\, g - F_N = 0 \qquad (5)$$

Dividing Eq. 5 by $\frac{1}{2} r\, a$:

$$C_L\, u^2 + \frac{y}{x} C_D\, u^2 + \frac{4}{3}\left(\frac{r_s}{r} - 1\right) g - 2\frac{F_N}{ra} = 0 \qquad (6)$$

$$A\left(\frac{dp\, t_w^{\frac{1}{2}+\frac{1}{n}}}{\sqrt{r}\, K^{\frac{1}{n}}}\right) + 1{,}732\left\{\left[\left(B \frac{K^{\frac{2}{n}}}{r\, dp^2 t_w^{\frac{2}{n}-1}}\right)^{0,67} + 2.70\right]^{1,14} \cdot \frac{d_P{}^2 t_w{}^{\frac{2}{n}}}{K^{\frac{2}{n}}}\right\} - \frac{4}{3}\left(\frac{r_s}{r} - 1\right) g - \frac{t_n}{r} = 0 \qquad (7)$$

where F_N is the normal force resultant from the axial fluid flow and τ_N is the normal tension.

MODEL RESULTS AND DISCUSSION

A commercial software[14] was used for the determination of velocity and stress profiles in eccentric annular laminar/turbulent flow of non-Newtonian fluids. Input data are bed height, flow rate, fluid properties and annular geometry (diameters and eccentricity), all obtained or controlled in the experiments. The run of the software for each experimental point allows the calculation of the shear stress at the interface solids bed – fluid for a given bed height.

The calculated shear stresses and the coefficients A and B obtained by Martins et al.[8] for the CMC solutions (at the 3 different concentrations) were now used in Eq. 7 to solve it for the normal force terms for the different polymers.

Table 2 shows the contribution of the lift, drag, buoyancy weight and normal stresses for each concentric experiment. Table 3 shows the results for the eccentric annulus.

Results for the concentric case indicate that the effect of the normal stresses increase from the XC to PHPA tests, qualitatively confirming the rheological results observed in Fig.2. The effect of polymer concentration is also coherent with the expected. The same tendency is observed at the eccentric tests where the total force actuating in the particle for the incipient motion condition is higher than in the analogous concentric case.

Table 2 - Contribution of the lift, drag, buoyancy weight and normal stresses for concentric annulus

Fluid	Viscosity	Lift		Drag		Buoyancy		Gravity		Normal	
		dyn	%	dyn	%	dyn	%	dyn	%	dyn	%
CMC	high	805	8.7	8064	86.9	122	1.3	288	3.1	0	0
CMC	average	578	4.7	11427	92.0	122	1.0	288	2.3	0	0
CMC	low	582	2.3	24330	96.1	122	0.5	288	1.1	0	0
PHPA	high	2211	1.4	39844	25.2	122	0.1	288	0.2	115701	73.2
PHPA	average	3132	0.4	148617	21.2	122	0.0	288	0.0	547923	78.3
PHPA	low	799	1.1	38227	53.7	122	0.2	288	0.4	31733	44.6
XC	high	2885	1.1	61062	22.3	122	0.0	288	0.1	209636	76.5
XC	average	665	2.8	14847	62.1	122	0.5	288	1.2	8001	33.4

Table 3 - Contribution of the lift, drag, buoyancy weight and normal stresses for concentric annulus

Fluid	Viscosity	Lift		Drag		Buoyancy		Gravity		Normal	
		dyn	%	dyn	%	dyn	%	dyn	%	dyn	%
CMC	high	993	7.9	11095	88.8	122	1.0	288	2.3	0	0
CMC	average	867	3.7	21988	94.5	122	0.5	288	1.2	0	0
CMC	low	602	2.3	25538	96.2	122	0.5	288	1.1	0	0
PHPA	high	3878	1.8	98126	46.0	122	0.1	288	0.1	111000	52.0
PHPA	average	3050	1.1	142811	51.3	122	0.0	288	0.1	132000	47.4
PHPA	low	757	1.7	35404	81.8	122	0.3	288	0.7	6730	15.5
XC	high	1870	3.6	30368	58.6	122	0.2	288	0.6	19200	37.0
XC	average	2131	1.5	83776	57.3	122	0.1	288	0.2	59900	41.0

Chin[15] presents a detailed study concerning the development of fluid velocity profiles in an eccentric annular laminar flow based on a Herschell-Bulkley model. For annular flows in the absence of a solids bed, there is a maximum Yield point, above which stagnant regions are formed in the narrow portions of the annulus. In this case, the eccentricity governs the velocity distribution in the annular cross section. When a solids bed is present, the eccentricity will be important in the erosion capacity of the carrier fluid, as verified in the experiments. The inter relation between rheology and eccentricity is more pronounced where low bed heights are low enough to form stagnant regions.

The previous theoretical work discussed is sufficient to support the following experimental observations:

- A same non Newtonian fluid will be able to erode more solids in the concentric annulus than in the eccentric. One fact is more pronounced in the fluids which present significatively high yield stresses (XC and PHPA solutions at average and high viscosities). For CMC fluids and XC and PHPA fluids at low viscosities, the eccentricity effect is less pronounced and this fact is expected by the low values of yield stresses which tend to form small stagnant regions.

Comparing the behaviour of the different polymers at a "same viscosity", the CMC solutions behaved better than XC and PHPA.

The influence of elasticity in the solids bed erosion is complex. The proposed model shows the increase of the normal stress contribution with the fluids which present higher first normal stress differences. These are exactly the fluids which delayed the incipient motion conditions in relation to the model proposed by Martins et al.[8]

CONCLUDING REMARKS

- The role of fluid rheolgical properties on the erosion of a solids bed deposited in the lower portions of a horizontal annulus was analyzed, based on an extensive experimental work involving rheological characterization and solids transport tests. The different performance of 3 types of polymer solutions was justified by the existence of normal stresses resultant from the viscoelastic properties of the fluids.
- Additional effort should be spent in the determination of reliable elastic properties of polymer type drilling fluids.
- Annular eccentricity also plays a major role in the process, especially when high yield stress fluids are concerned. In this case there is tendency to form stagnant regions in the lower portions of an eccentric annulus.
- The mechanistic model proposed proved to be useful to predict critical shear stresses in the interface solids bed – carrier fluid. A more complete model, including the coupling of erosion and sedimentation processes, is under development and aims the analysis of rheological effects in the complete drilling process.

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