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An improvement of thixotropic behavior prediction of bentonite water based drilling fluids

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ABSTRACT

This study is the continuation of the work generated by Production and Drilling Research Project (PDRP) at New Mexico Institute of Mining and Technology with the purpose of developing a rheological model to quantitatively predict the thixotropic behavior. In order to do this, a number of shear relaxation tests were conducted at different fluid temperatures and bentonite concentrations. Five empirical correlations, which are the functions of fluid temperature and bentonite concentration, were attained based on the experimental data. These correlations are to calculate the five parameters existing in the PDRP's model namely pre-exponential coefficient τ_t, inverse relaxation time $1/T_t$, equilibrium yield point τ_{ye}, equilibrium consistency index K_e, and equilibrium flow behavior index m_e. With these five correlations, the rheological model to characterize the thixotropic behavior of a water based drilling fluid at any given bentonite concentration and fluid temperature is completely determined without the need of carrying other tests. The completed rheological model is then combined with the momentum equations to predict frictional pressure loss in pipe or annular flow. The results of this work make the prediction of thixotropic behaviors as well as the flowing bottom-hole pressure much simpler and quicker and hence help drillers' response faster and more accurate during drilling operations.

1. Introduction and literature reviews

The accurate prediction of frictional loss in an annulus plays a pivotal role in any drilling operations. This estimation can be applied to determine the equivalent circulating density (ECD) as well as the kick-off pump pressure, which are the paramount parameters in mud circulation and well control operations. However, the selection of suitable rheological models has always been a problem affecting this prediction. Conventional hydraulics models commonly regard drilling fluids to be time-independent fluids. These models hypothesize that if the shear rate applied to the fluid is kept constant, the shear stress exerted on the fluid will be constant over time. Therefore, the frictional pressure loss is also unchanging with time. However, in reality, most water based drilling fluids which contain bentonite as clay

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mineral, exhibit a pronounced time and shear dependencies. The bentonite clay particles are electrically changed and interact to form a loose "house-of-cards" structure that is responsible for the gelling characteristics of the fluid when at rest, and its thinning behavior when sheared (Jenekhe et al., 1989). This structure and the rheological properties show a time-dependent response to shear (i.e. thixotropy).

Thixotropy can be described as the reversible, isothermal transformation of fluid from a colloidal solution or liquid to a gel or solid form. Consequently, the fluid's viscosity decreases over time, due to structure rearrangement, when the fluid is subjected to a constant rate of shear (Darley and Gray, 1988).

For instance, when the mud circulation is halted, the drilling fluid tends to be gel up and leads its viscosity to increase. To resume circulation, a higher pump pressure must be required to destroy the built-up gel structure. The extra pressure is a sign of the change in the properties of the fluid as it was at rest due to its thixotropy. For narrow mud weight window formations, a significant extra pressure could cause formation fracturing or in worse case, breakdown of formation. Thus, detailed researches on fluid thixotropy may offer a better a drilling hydraulic control.

The theological properties of drilling fluid are subject to continuous modification as the fluid circulates around the wellbore. The changes are caused by shearing, temperature, pressure and chemical modification of the fluid as it contacts various formations on its way to the surface (Dairanieh and Lahalih, 1988).

Tehrani (Tehrani and Popplestone, 2009) modified Cheng-Evans model (Cheng and Evans, 1965) and introduced the following equation to characterize the thixotropy effect of drilling fluids in Equation (1).

$$\tau(t) = \lambda(t)\tau_y + [\eta_\infty + c\lambda(t)]\dot{\gamma}^m \quad (1)$$

where τ_y is yield point, λ(t) is the structure parameter, η_∞ is the viscosity of unstructured fluid, $\dot{\gamma}$ is shear rate and m is the flow behavior index. The authors proposed to perform four types of tests in order to identify nine constant parameters in Equation (1). Thus, the application of the model is restricted in engineering perspective.

Pivnicka and his team at the Production and Drilling Research Project (PDRP) (Pivnicka et al., 2015) conducted many shear relaxation tests and simplified Tehrani's model as expressed in Equation (2).

$$\tau(t) = \underbrace{\tau_t e^{-\left(\frac{t}{T_t}\right)}}_{\text{Transient}} + \underbrace{\tau_{ye} + K_e\dot{\gamma}^{m_e}}_{\text{Equilibrium}} \quad (2)$$

where τ_t is the pre-exponential coefficient, $1/T_t$ is the inverse relaxation time, τ_{ye} is the equilibrium yield point, K_e is the equilibrium consistency index, $\dot{\gamma}$ is shear rate and m_e is the equilibrium flow behavior index.

This model is referred as PDRP's model in this paper. The authors made some assumptions to reduce the number of constant parameters in Tehrani's model from nine to five. They also proposed to use only the shear relaxation test to attain the five constant parameters.

Following the developing of PDRP's model, the main objective of this work is to determine empirical correlations to obtain the five constant parameters in PDRP's model at different fluid temperatures and bentonite concentrations. These correlations provide a simple and approximately accurate way to attain PDRP's parameters without further need of carrying out the shear relaxation tests.

2. Model development

Recall PDRP's model as shown in Equation (2) in the Introduction section, where τ_t is the pre-exponential coefficient, $1/T_t$ is the inverse relaxation time, τ_{ye} is the equilibrium yield point, K_e is the equilibrium consistency index, $\dot{\gamma}$ is shear rate and m_e is the equilibrium flow behavior index.

Generally speaking, the thixotropic behavior or time-dependent of drilling fluids can now be characterized by using Equation (2) if the five PDRP's model parameters are known. Note that these five parameters are the functions of fluid temperature and bentonite concentration.

In order to predict frictional pressure losses in annuli, one has to combine the rheological equation, described by Equation (2), and the momentum equation. For fully-developed, isothermal, steady-state and incompressible fluid, the relationship between wall shear stress, τ_w, and frictional pressure loss gradient, dp/dL, in an annulus can be expressed as:

$$\tau_w = \frac{D_H}{4}\left(-\frac{dp}{dL}\right) \quad (3)$$

where $D_H = D_2 - D_1$ is the hydraulic diameter and D_1, D_2 is the outer pipe diameter of the drillpipe and inner diameter of the casing respectively;

Combining the Equation (2) and Equation (3) gives:

$$-\frac{dp}{dL}(t,\dot{\gamma}) = \frac{4}{D_2 - D_1}\left[\tau_1(\dot{\gamma})e^{-\left(\frac{t}{T_t}(\dot{\gamma})\right)} + \tau_{ye} + K_e\dot{\gamma}^{m_e}\right] \quad (4)$$

In general, from shear relaxation tests, the five parameters in PDRP's model can be obtained for a specific temperature and specific bentonite concentration. If the well geometry and the fluid circulation rate are given then solving Equation (4) can estimate the frictional pressure loss in an annulus.

3. Determination of PDRP Model's Parameters Based on Shear Relaxation Tests

The objective of this section is to attain five empirical correlations, which can be utilized to calculate the five parameters in PDRP model. In order to achieve these correlations, a series of shear relaxation tests were carried out by using the AR-1500EX, a two parallel-plate rheometer. Bentonite at different weight concentrations and different temperatures were varied during the tests. The test procedure can be summarized as follows:

- Mix bentonite and water over a period of fifteen minutes to obtain a desired weight bentonite concentration;
- Rest the sample for 24 hours under room temperatures;
- Transfer carefully the sample to a sample plate;
- Heat the sample up to the required temperature and pre-shear at a high speed. Leave them at rest for an hour;
- Exert a constant shear rate on the sample and record the change of shear stress with time. The time interval of recording data is 2 seconds for the first 10 minutes and 10 seconds for the rest.

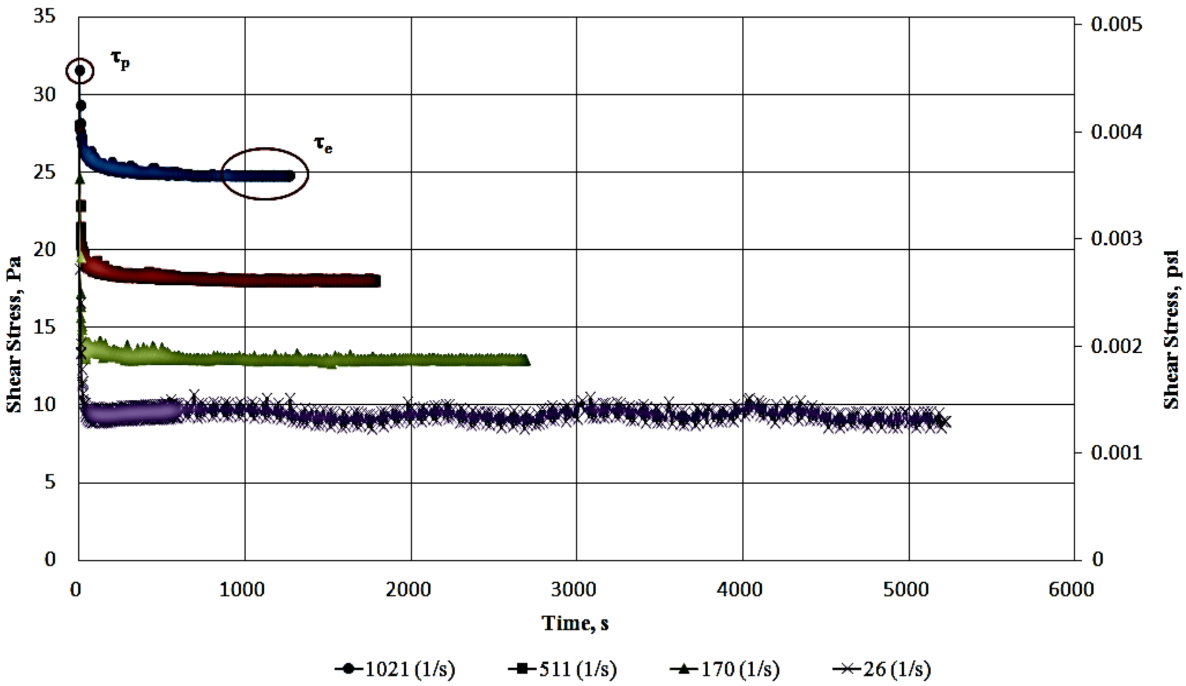

Figure 1. Shear stress relaxation test result

Figure 1 shows the results of the typical shear stress relaxation tests for a bentonite concentration of 5%wt , a fluid temperature of 77°F and various shear rates of 26, 170, 511 and 1021 (s^{-1}). Each test, the shear rate was kept constant and the shear stresses were recorded until the equilibrium shear stress was attained. The data reveals that as a constant shear rate is applied to the sample, the shear stress increases until it reaches a maximum value, which is defined as the shear stress peak (τ_p). Then the magnitude of shear stress reduces with time and finally reaches to the equilibrium value, τ_e. Theoretically, the peak stress is the maximum stress required to destroy the gel structure of the fluid formed when it is at rest. The transient stress data from the peak to equilibrium stresses are used to determine the first two transient parameters τ_t and $1/T_t$ for the fluid temperature of 77°F and bentonite concentration of 5%wt in the PDRP's model. Furthermore, the plot also shows that the rate of structure breakdown depends on the shear rate, which was described by Moore (Moore,, 1959). In other words, the structural breakdown rate is higher for a higher shear rate along with shorter time to reach to equilibrium state.

From the Figure 1, four different equilibrium stresses at four different shear rates were attained and plotted in Figure 2. It is obvious that the fluid behavior under equilibrium conditions complies the Herschel-Bulkley model. Therefore, the three equilibrium parameters τ_{ye}, K_e and m_e in PDRP's model at the fluid temperature of 77°F and bentonite concentration of 5%wt are obtained by using the log-log technique.

Herschel-Buckley model for fluid under equilibrium conditions can be written:

$$\tau = \tau_{ye} + K_e \dot{\gamma}_e^{\,m_e} \qquad (5)$$

Rearranging Equation (5) and taking natural log of both sides achieve as

$$\ln(\tau - \tau_{ye}) = m_e \ln \dot{\gamma} + \ln K_e \qquad (6)$$

The plot of $\ln(\tau - \tau_{ye})$ against $\ln \dot{\gamma}$ was developed. The value of equilibrium yield point, τ_{ye}, was adjusted to obtain the highest R^2. The value of τ_{ye}, K_e, m_e were identified at this maximum R^2 value. The slope of trend line is m_e and the y-intercept is $\ln K_e$.

In summary, from the shear relaxation tests, the five parameters in PDRP's model are identified for the fluid temperature of 77°F and bentonite concentration of 5%wt.

The same experimental procedure and data analysis were conducted for two different bentonite concentrations, 4%wt and 5%wt and for three different fluid temperatures, 77°F, 90°F and 100°F. At each combination between fluid temperature and bentonite concentration, the five parameters in PDRP's model were computed and presented in Table 1.

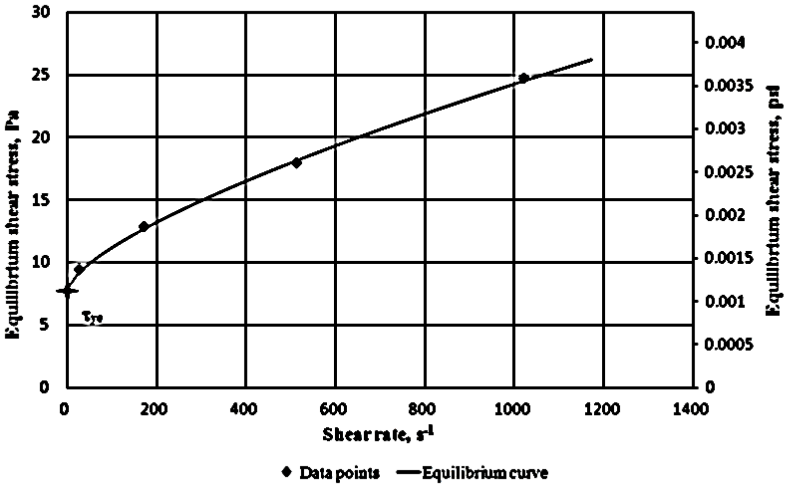

Figure 2. Equilibrium curve of 5%wt bentonite fluid at 77°F

From the collected data in Table 1, five empirical correlations for calculating five parameters in the PDRP's model were derived. These correlations were obtained by using the Regression Add-in in Excel in such a way that the difference between two plots is minimized to achieve the best result possible. The five correlations are presented as follows in Table 1.

Table 1. PDRP Model's parameters at different temperatures and bentonite

Concentration (%)	Temperature (°F)	Shear rate (s^{-1})	τ_t (Pa)	$1/T_t$	τ_e	K_e	m_e
4	77	0	0	0	2.55	0.149485	0.6775
		26	6.92	0.012	2.55	0.149485	0.6775
		170	7.55	0.015	2.55	0.149485	0.6775
		511	6.62	0.015	2.55	0.149485	0.6775
		1021	4.29	0.026	2.55	0.149485	0.6775
	90	0	0	0	2.48	0.131734	0.6859
		26	4.21	0.016	2.48	0.131734	0.6859
		170	6.35	0.04	2.48	0.131734	0.6859
		511	5.78	0.045	2.48	0.131734	0.6859
		1021	3.77	0.065	2.48	0.131734	0.6859
	100	0	0	0	2.46	0.119096	0.6959
		26	2.64	0.017	2.46	0.119096	0.6959
		170	5.5	0.06	2.46	0.119096	0.6959
		511	4.92	0.08	2.46	0.119096	0.6959
		1021	3.02	0.1	2.46	0.119096	0.6959
5	77	0	0	0	8.08	0.160251	0.6664
		26	9.42	0.007	8.08	0.160251	0.6664
		170	11.91	0.011	8.08	0.160251	0.6664
		511	10.2	0.015	8.08	0.160251	0.6664
		1021	7.06	0.019	8.08	0.160251	0.6664
	90	0	0	0	7.18	0.136395	0.6694
		26	5.87	0.009	7.18	0.136395	0.6694
		170	8.84	0.016	7.18	0.136395	0.6694
		511	8.57	0.032	7.18	0.136395	0.6694
		1021	5.84	0.047	7.18	0.136395	0.6694
	100	0	0	0	7	0.118331	0.68
		26	3.06	0.011	7	0.118331	0.68
		170	7.68	0.023	7	0.118331	0.68
		511	7.52	0.043	7	0.118331	0.68
		1021	4.9	0.07	7	0.118331	0.68

$$\frac{1}{T_t} = 0.002406\dot{\gamma} + 0.04435T - 0.937C - 2.9 * 10^{-5}\dot{\gamma}T - 5.1 * 10^{-4}\dot{\gamma}C - 8.58 * 10^{-3}TC + 6.2 * 10^{-6}\dot{\gamma}TC - 0.41999\sqrt{\dot{\gamma}} - 1.737\sqrt{T} + 0.04663\sqrt{\dot{\gamma}T} + 0.18717\sqrt{\dot{\gamma}C} + 0.76521\sqrt{TC} - 0.02075\sqrt{\dot{\gamma}TC} + 4.80536 \quad (7)$$

$$\tau_t = 0.04964\dot{\gamma} - 1.67564T + 55.62283C - 3.8 * 10^{-4}\,\dot{\gamma}T - 9.47 * 10^{-3}\,\dot{\gamma}C + 0.42513TC + 2.64 * 10^{-5}\,\dot{\gamma}TC - 2.64576\sqrt{(\dot{\gamma})} + 78.63155\sqrt{T} + 0.06758\sqrt{(\dot{\gamma}T)} + 0.24551\sqrt{(\dot{\gamma}C)} - 41.882\sqrt{TC} + 0.102646\sqrt{(\dot{\gamma}TC)} - 173.472 \quad (8)$$

$$\tau_{ye} = 0.172256T + 8.844687c - 0.04406TC - 32.5274 \quad (9)$$

$$K_e = 6.76 * 10^{-4}T + 4.937 * 10^{-2}C - 5 * 10^{-4}TC + 0.053746 \quad (10)$$

$$m_e = 1.668 * 10^{-3}T + 4.973 * 10^{-3}C - 2.2 * 10^{-4}TC + 0.596011 \quad (11)$$

where τ_t is the pre-exponential coefficient, $1/T_t$ is the inverse relaxation time, τ_{ye} is the equilibrium yield point, K_e is the equilibrium consistency index, m_e is the equilibrium flow behavior index, $\dot{\gamma}$ is shear rate, T is temperature and C is Bentonite concentration.

Figures 3, 4, and 5 demonstrate the validation of Equations (7) – (11) by using the shear relax ation data. All the correlations above are consistent well with the experimental data with the coefficients of determination (R^2) of more than 97%.

Table 2. Coefficients of determination for the correlations

Equations	Coefficient of determination (R^2)
Equation (7)	0.989
Equation (8)	0.985
Equation (9)	0.998
Equation (10)	0.995
Equation (11)	0.971

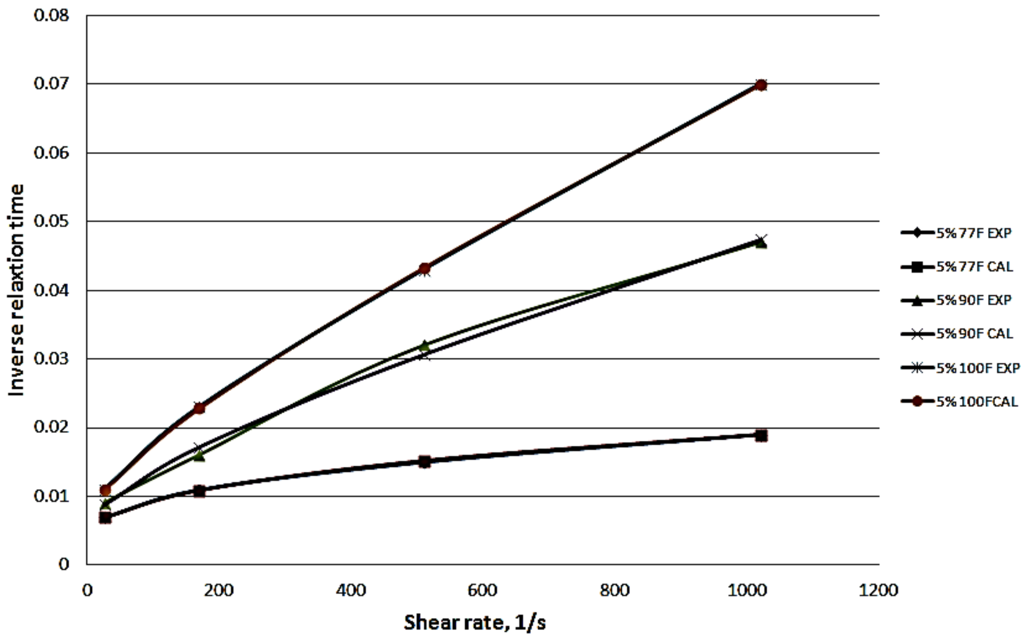

Figure 3. Comparison of the inverse relaxation time coefficients obtained from experiments and data obtained from Equation (7) for 5%wt bentonite fluid

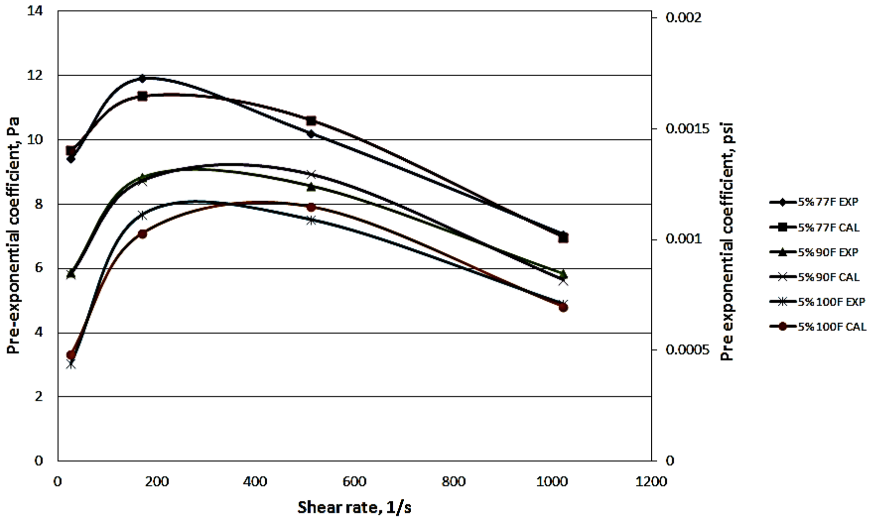

Figure 4. Comparison of pre-exponential coefficients obtained from experiments and data obtained from Equation (8) for 5%wt bentonite fluid

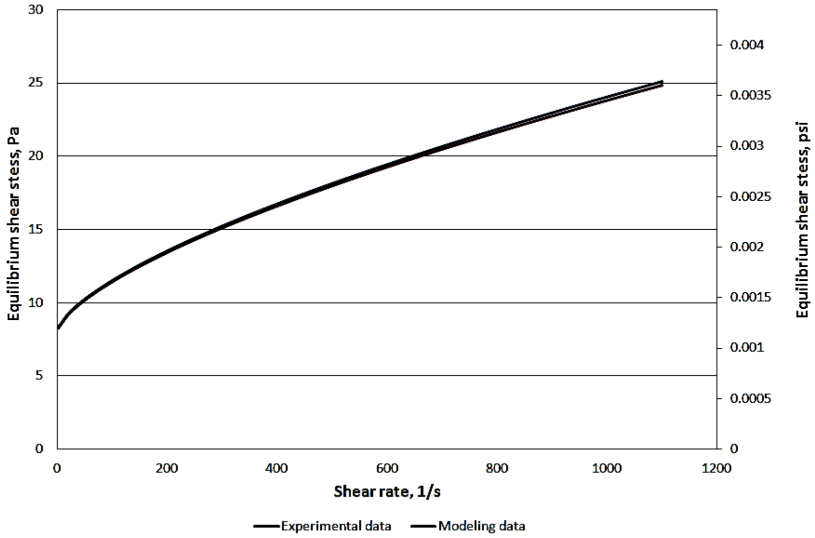

Figure 5. Equilibrium curves generated from experimental data and modeling data

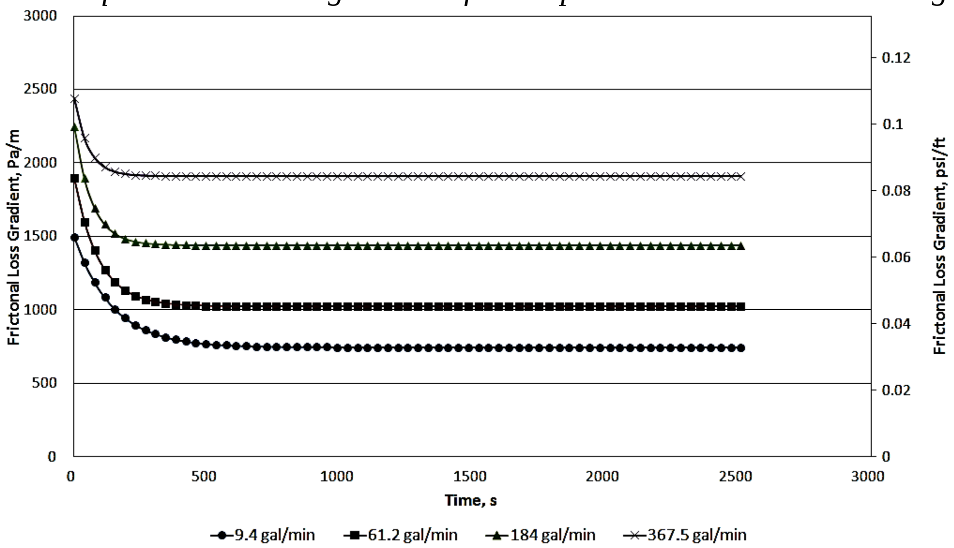

Figure 6. Frictional pressure gradient prediction in annuli (5%wt bentonite fluid and 77^{o}F)

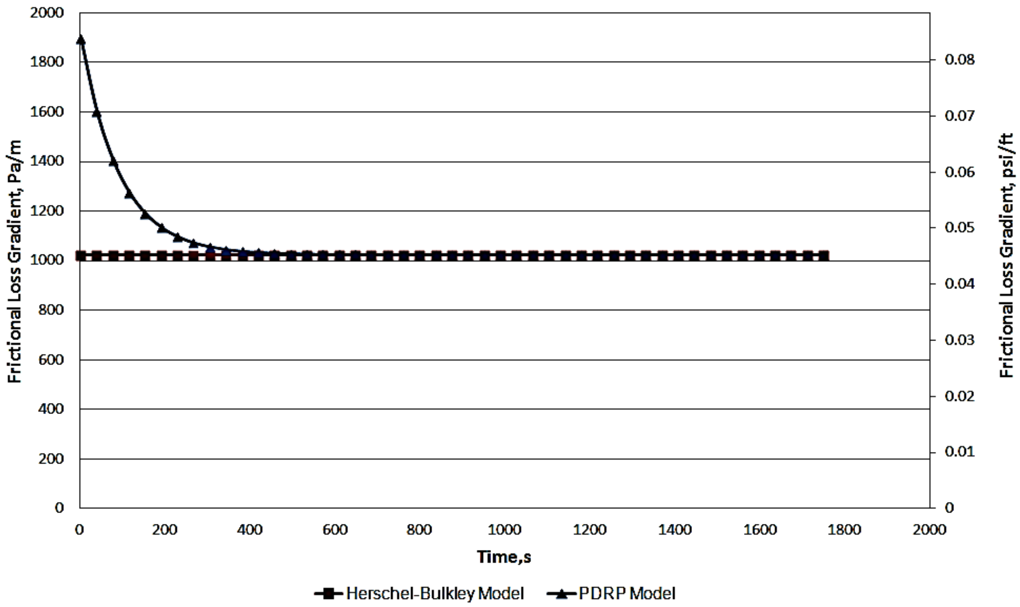

Figure 7. PDRP's model and Herschel Bulkley model prediction for 5%wt bentonite fluid, 77°F temperature and 170 s^{-1} shear rate

At the bentonite concentration of 5% and fluid temperature of 77°F, using Equations (9), (10), and (11) give the values of τ_{ye}, K_e, and m_e of 8, 0.1602 and 0.665 respectively. Applying these three parameters to Equation (2) under equilibrium conditions (the transient term reaches to zero), one can plot the predicted relationship between equilibrium shear stress and shear rate as shown in Figure 5. The reliability of Equations (9), (10), and (11) is also shown in Figure 5 by comparing the predicted curve with that of generated from the experimental data. The results reveal a very good match between the two curves with the errors less than 3%.

4. Frictional Pressure Loss Gradient Prediction

By using the Equations (7) - (11) in conjunction with the well geometry and circulation flow rate, the frictional pressure loss gradient in the annulus can be obtained by solving Equation (4). Figure 7 shows the frictional pressure loss gradient prediction for the fluid temperature of 77°F, bentonite concentration of 5%wt, outer pipe diameter, D_1, of 2 in., inner casing diameter, D_2, of 4 in., and circulation flow rates of 9.4, 61.2, 184 and 367.5 gal/min respectively. The values of τ_t, $1/T_t$, τ_{ye}, K_e, and m_e are calculated by using Equations (7) – (11). Clearly, the PDRP model captures well the thixotropic behavior of bentonite drilling fluids by showing the pressure peak following by the pressure decline then the pressure equilibrium. The model reveals that the maximum difference between the pressure gradient peak and the equilibrium pressure gradient is about 67%. In other words, the conventional hydraulic model may underestimate as high as 67% the frictional pressure loss in the wellbore.

The selection of inappropriate hydraulic models can make errors in calculating frictional loss. For conventional hydraulic models, they disregard the change in fluid structure and only use the equilibrium shear stresses to calculate the frictional drops. Therefore, there is no variation in the magnitude of frictional gradient during drilling operations. Consequently, the predictions of steady-state models are considerably underestimated the dynamic bottom-hole pressure in the start-up period.

Figure 7 illustrates the difference in results of calculating pressure loss gradient using PDRP's model and Herschel-Bulkley model, which is widely used for hydraulic calculations. Two models have the same results when the fluid has reached the equilibrium conditions. However, the significant difference among models' results occurs in an early stage as the fluid structure has broken up. At this point, the pressure gradient predicted by PDRP's model is 1897.3 Pa/m (0.084psi/ft), which is twice higher than the value predicted by Herschel Bulkley model. The net difference between the results' models is approximately 874.4Pa/m (0.04psi/ft), which corresponds to a difference of $2.757903.10^6$ Pa (400psi) for a 10,000ft depth wellbore. After that, the pressure gradient decreases gradually to an equilibrium value of 1022.9Pa/m (0.045psi/ft).

5. Conclusion

- Oilfield drilling fluids, particularly bentonite fluids, exhibit a pronounced thixotropic behavior. The instinct of the thixotropy is the interaction of dynamic growth and break-down of structure within fluid.
- The effect of thixotropy is highly dependent on time, shear rate, temperature and bentonite concentration.
- Five different correlations to calculate the five constant parameters of PDRP's model were developed for water based bentonite drilling fluids. These correlations in conjunction with PDRP's model help to predict the maximum possible flowing bottomhole pressure (or ECD) and pressures under equilibrium conditions for any fluid temperatures and bentonite concentrations without the need of conducting rheological tests.
- Conventional model may underestimate the flowing bottomhole pressure as high as 67%. Using PDRP's model helps to improve the prediction and hence avoid drilling problems related to over bottomhole pressures such as fluid loss, formation damage, wellbore stability, etc.

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