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REDUCTION IN ANNULAR PRESSURE LOSS BY MUD RHEOLOGY CONTROL- A MEANS OF MUD PUMP PRESSURE OPTIMIZATION, A CASE STUDY OF A NIGER DELTA WELL

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AUTHORS' CONTRIBUTIONS

This work was carried out in collaboration between all authors. Author INO designed the study, wrote the protocol and interpreted the data. Author KCI anchored the field study, gathered the initial data and performed preliminary data analysis. Authors INO and UID managed the literature searches and produced the initial draft. All authors read and approved the final manuscript.

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ABSTRACT

This paper proposes two linear mathematical models for the reduction of annular pressure loss in a Niger Delta well- X, so that mud pump pressure is optimized. Data related to mud rheology, mud pump pressure, drill cuttings and the well geometry is available for well X which has already been drilled. The first linear model involves the reduction in pressure drop in the drill collar-casing annulus and the second linear model involves the reduction in pressure drop in the drill pipe-casing annulus. These models express reduced or critical annular pressure drops in terms of two mud rheological parameters- the yield point and plastic viscosity. For combined annular drill collar and drill pipe pressure loss, this paper proposes that the two linear mathematical models can be solved simultaneously to obtain optimum yield point and plastic viscosity of the drilling mud system to be employed for hole cleaning in the combined drill collar-casing and drill pipe-casing annulus. The Herschel-Bulkley model is employed as the rheological model that represents the properties of the drilling mud system analyzed and is generated for eight rheological cases each of the drill collar and drill pipe annular hole cleaning as well as two cases of the combined drill collar and drill pipe annular hole cleaning.

Keywords: Annular pressure loss; Mud rheology; pump pressure; critical annular pressure drop; optimum yield point; optimum plastic viscosity; Herschel Bulkley model.

NOMENCLATURES

V_{s-lam} = *Slip Velocity in laminar flow (ft/min)*
V_{s-turb} = *Slip Velocity in turbulent flow (ft/min)*
d_P = *Particle Diameter (inches)*
μ = *Equivalent mud viscosity*
pp = *Particle density (lb/gal)*

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MD = *Mud Density (lb/gal)*
CD = *Drag Coefficient*
Pl_a = *Total annular pressure loss, psi*
d_{casing} = *Casing inner diameter, inches*
L = *Casing length*
$V_{annular}$ = *Annular velocity, ft/min*
Pl_{dp} = *Pressure drop in the drill pipe-casing annulus*
Pl_{dc} = *Pressure drop in the drill collar-casing annulus*
L_{dc} = *Length of drill collar, ft*
V_{crit} = *Critical annular velocity, ft/min*
PV = *Plastic viscosity, cp*
YP = *Yield point, lb/100ft^2*
d_{dp} = *Diameter of drill pipe, in*
d_{dc} = *Diameter of drill collar, in*
d_{casing} = *Casing inner diameter, in*
τ = *Shear stress, lb/ft^2*
K = *Laminar flow consistency factor*
n = *Laminar flow behaviour index*
γ = *Drilling mud shear rate*
τ_y = *Yield Point, lb/100ft^2*

1. INTRODUCTION

Pressure is lost throughout the circulation path of the drilling mud from the mud pump through the drill pipe, the drill collar, the bit nozzles, drill collar-casing annulus, drill pipe-casing annulus and surface cuttings removal equipment. Total pressure loss is the sum of all pressure drops across these points and is equal to the mud pump pressure. The hydraulic horse power of the mud pump is a function of the mud pump rate and the pump pressure. The mud pump rate will determine the annular velocity at which cuttings are transported to the surface. The hydraulic horsepower of the mud pump and therefore the mud pump pressure should be such that the cuttings are efficiently removed away from the drill bit so that the bit drills ahead without difficulty. The greatest part of the mud pump pressure should therefore be available for the operations of the drill bit.

The hole cleaning characteristics of the drilling mud system used on the rotary drilling rig is one of its major functions and ensures that the drilling operation progresses without difficulty. The main properties of the mud which guarantee this function are called the mud rheological properties and are related to its flow. Annular Pressure loss can be estimated through equations expressed as functions of mud rheological and hydraulic properties; length of drill pipe and drill collar; and diameter of drill collar, drill pipe and casing. To ensure a reduced annular pressure loss and therefore mud pump pressure optimization, the mud rheological properties are the only input parameters in the pressure loss equation that can be optimally controlled. The mud hydraulic properties which include the mud pump rate, pump pressure and annular fluid velocity can also be controlled but their control is limited to the hydrostatic horsepower of the mud pump. The length and diameter of the drill collar, drill pipe and casing cannot be controlled and depend on the total depth reached and the geometric requirements of the drilled hole. The mud rheological properties analyzed include the yield point and plastic viscosity, the annular laminar flow behaviour index (na) and the annular laminar flow consistency factor (Ka). The plastic viscosity is the measure of that part of the drilling mud’s resistance to flow caused by mechanical friction between the solids in the mud, the solids and liquid phase of the mud, and the shearing layers within the mud. The yield point is a measure of attractive forces between the surface charges or ions on the solid particles used to formulate the drilling mud system. The yield point is therefore a function of the surface properties of mud solids, the volume concentration of these solids and the concentration and type of ions within the fluid phase. The plastic viscosity and yield point can be determined by mathematical equations expressed in terms of the dial readings of a Fann viscometer or drilling mud rheometer- a laboratory as well as field site equipment used to measure mud rheological properties. The annular laminar flow behaviour index (na) and the annular laminar flow consistency factor (Ka) give a measure of the shear thinning characteristics of the drilling mud system. Shear thinning is a phenomenon used to describe the ability of the drilling mud system to retain its viscosity and therefore hole cleaning function, when circulating pressures are low, or at low rates of shear prevalent in the annulus. The objective of this paper is therefore to obtain optimum mud rheology estimated at the annular critical pressure drop which will ensure an efficient hole cleaning and also optimize mud pump pressure.

Lim et al. [1] discovered that optimizing the ratio of the pressure loss across the bit nozzles to the total circulating pressure loss for the two methods of drilling hydraulics optimization which they studied (the hydraulic horsepower and jet impact force) will lead to an efficient hole cleaning in vertical and near vertical wellbores. Wright et al. [2] discovered that optimizing mud pump hydraulics for optimum hole cleaning required selection and design of optimum bit nozzle sizes, in their study of the energy cost and economic analysis of two hydraulic optimization designs- Hydraulic Horse Power and Jet Impact Force. Simon [3] discovered that an accurate modelling of pressure losses was necessary in the drilling of re-entry wells where a small safety margin exists between optimal drilling parameters and wellbore stability. He investigated the influence of well geometry and accuracy of fluid rheological properties modelling to the distribution of pressure losses in a slimhole well. Guarneri et al. [4] demonstrated that the drilling optimization process can be improved if mud rheology is considered as a product rather than an input. They defined drilling optimization criteria which considered various drilling hydraulics constraints such as drilling margin based on fracture gradient and mud weight, hole cleaning requirements, pump hydraulic power, downhole tool limitations, pump limitations, and wellbore erosion. They determined Herschel-Bulkley rheological properties and flow rate required to satisfy the defined optimization criteria and constraints. Ogunrinde et al. [5] discovered that optimizing mud hydraulic properties was the means for efficient hole cleaning in deviated and horizontal wells. They developed a model which is used to determine an optimum flow rate and rate of penetration for efficient hole cleaning in critical hole angles between 45° and 60°. Noah [6] discovered that optimizing drilling mud rheological and hydraulic properties will reduce cuttings bed height in horizontal and high angle wells. He achieved mud hydraulic properties optimization by varying mud pump rate between 200 and 400 gallons per minute to study changes in cuttings bed height as a function of time. Ghasemikafrudi et al. [7] numerically modelled the velocity profile of the drilling mud required for accurate prediction of pressure drop. They considered the effects of velocity, mud properties, and fraction of solid phase volume of the drilling mud on pressure drop.

2. METHODOLOGY

The methodology presented in this paper involves the use of established correlations and equations defined using hole cleaning parameters to:

1. Evaluate the impact of rheology on hole cleaning.
2. Optimize mud pump pressure by minimizing drill pipe and drill collar annular pressure loss based on sensitivities carried out on available rheological data.
3. Calculate critical annular velocity as a value equal to the slip velocity.
4. Obtain optimized Herschel-Bulkley rheological models for annular drill collar and drill pipe as well as combined drill collar and drill pipe annular hole cleaning.

A case study well- X which has already been drilled is used in this paper to demonstrate mud pump pressure optimization and the impact of rheology on annular hole cleaning. The available data is presented in Table 1 under different categories.

Table 1. Data summary

Mud rheology		**Pressure/rate**		**Well X geometry**		**Drill cuttings**	
Plastic viscosity	6 cp	Pump pressure	346psi	Open hole diameter	12 inches	Cutting density	22 lb/gal
Yield point	18 lb/100ft^2	Pump rate	760gpm	Casing inner diameter	13.375 inches	Cutting diameter	0.2 inches
Mud weight	8.9 lb/gal			Casing length	374.2 metres		
Dial reading at 3rpm (5.11sec^{-1})	7			Drill pipe length	318.3 metres		
Dial reading at 6rpm (10.22 sec^{-1})	8			Drill collar length	55.9 metres		
Dial reading at 100rpm (170.3 sec^{-1})	16			Drill pipe outer diameter	5 inches		
Dial reading at 200rpm (340.7 sec^{-1})	19			Drill collar outer diameter	8 inches		
Dial reading at 300rpm (511 sec^{-1})	24						
Dial reading at 600rpm (1022 sec^{-1})	30						

3. IMPACT OF RHEOLOGY ON HOLE CLEANING IN THE ANNULUS

Mud rheology is the most important factor that affects hole cleaning. For efficient annular hole cleaning, an optimal rheological description of the mud is required to ensure a continuous upward movement of the cuttings. The drilling mud should be such that exhibits very high viscosities at low rates of shear. This property of the mud is known as shear thinning and drilling mud systems that exhibit shear thinning characteristics are called pseudo plastic drilling mud systems. Laminar flow of drilling mud is usually prevalent in the annulus and result in low shear rates of the mud. In this paper, four parameters are used to demonstrate the impact of rheology on hole cleaning and include the yield point (YP), plastic viscosity (PV), the annular laminar flow behaviour index (n_a) and the annular laminar flow consistency factor (Ka). YP is the main rheological parameter that causes cuttings to come out of hole, while PV has small impact. Drilling muds with a very high yield point and very low plastic viscosity values are optimum for hole cleaning. On the other hand, a drilling mud with very low laminar flow behaviour index and high laminar flow consistency factor values exhibit a high degree of shear thinning and is therefore optimum for hole cleaning. The following equations show the relationship between, YP, PV, n_a and Ka.

$$\mathrm{PV} = \Theta600 - \Theta300 \tag{1}$$

$$\mathrm{YP} = \Theta300 - \mathrm{PV} \tag{2}$$

Where $\Theta300$ and $\Theta600$ are the dial readings at 300 and 600 spindle revolutions per minute usually measured using a Fann Viscometer or Rheometer.

Substituting the value of plastic viscosity, PV given in equation 1 into equation 2, gives:

$$\mathrm{YP} = 2(\Theta300) - \Theta600 \tag{3}$$

Also $\Theta300$ and $\Theta600$ dial readings can be expressed as functions of the plastic viscosity and yield point as shown:

From equation 2,

$$\Theta300 = \mathrm{YP} + \mathrm{PV} \tag{4}$$

Multiplying equation 4 by 2 and rearranging equation 3 gives:

$$2(\Theta300) = 2\mathrm{YP} + 2\mathrm{PV} \tag{5}$$

$$2(\Theta300) - \Theta600 = \mathrm{YP} \tag{6}$$

Subtracting equation 6 from equation 5 gives the dial reading at 600 rpm as:

$$\Theta600 = 2\mathrm{PV} + \mathrm{YP} \tag{7}$$

The relationships for the annular laminar flow behaviour index, n_a and annular laminar flow consistency factor, Ka are mathematically stated below:

$$\mathrm{n_a} = 0.5 \log\left(\frac{\Theta300}{\Theta3}\right) \tag{8}$$

$$\mathrm{K_a} = \frac{5.11 \times \Theta300}{511^{\mathrm{n_a}}} \tag{9}$$

The dial reading at 3 rpm, $\Theta3$, is an important mud rheological property because it replicates the low shear rate of the mud in the annulus. When these equations are applied using the hole cleaning data presented in Table 1, the following values of the mud rheological parameters are obtained:

$$\mathrm{PV} = \Theta600 - \Theta300 = 30 - 24 = 6\ \mathrm{cp}$$
$$\mathrm{YP} = 2(\Theta300) - \Theta600 = (2 \times 24) - 30$$
$$= 18\ \mathrm{lb/100ft^2}$$
$$\mathrm{n_a} = 0.5 \log\left(\frac{24}{7}\right) = 0.27$$
$$\mathrm{Ka} = \frac{5.11 \times 24}{511^{0.27}} = 22.77$$

4. PUMP PRESSURE OPTIMIZATION

The hydraulic horse power of the mud pump circulating mud at a rate of 760 gallons per minute at 346 psi is given by the relationship below:

$$\text{Hydraulic Horse Power} = \frac{\mathrm{Q\Delta P}}{1714} \tag{10}$$

$$= \frac{760 \times 346}{1714} = 153.42\mathrm{hp}$$

The power rating of the mud pump is low. The main focus of this paper is therefore to optimize the pump pressure and hence the hydraulic horse power of the mud pump. The following steps will be taken to achieve this objective:

Step 1:

Calculate the slip velocity of the drill cutting in laminar and turbulent flow. The laminar flow regime is prevalent in the drill pipe annulus and the turbulent flow regime is prevalent in the drill collar annulus. The following relationships are used to calculate slip velocity in laminar and turbulent flow:

Slip velocity in laminar flow:

$$\mathrm{V_{s-lam}} = 175.2 \times \mathrm{d_p} \times \left[\frac{(\mathrm{pp-MD})^2}{\mu \times \mathrm{MD}}\right]^{0.333} \quad (11)$$

80270H Rev. B [8]

Slip velocity in turbulent flow:

$$\mathrm{V_{s-turb}} = 113.4 \times \left[\mathrm{d_p}\left(\frac{\mathrm{pp\ -MD}}{\mathrm{CD} \times \mathrm{MD}}\right)\right]^{0.5} \quad (12)$$

80270H Rev. B [8]

The drag coefficient, CD is the frictional drag between the fluid and the particle. In turbulent flow, the drag coefficient is 1.5. In laminar flow, the equivalent mud viscosity (μ) will affect the slip velocity and is given by the following relationship:

$$\mu = \frac{90000 \times \mathrm{Pl_a} \times \left(\mathrm{d_{casing}} - \mathrm{d_p}\right)^2}{\mathrm{L} \times \mathrm{V_{annular}}} \quad (13)$$

80270H Rev. B [8]

From the available data presented in Table 1, slip velocity of drill cuttings in laminar flow prevalent in the drill pipe annulus can be calculated in terms of equivalent mud viscosity, μ as:

$$\mathrm{V_{s-lam}} = 175.2 \times 0.2 \times \left[\frac{(22-8.9)^2}{\mu \times 8.9}\right]^{0.333}$$

$$\mathrm{V_{s-lam}} = \frac{93.87}{\mu^{0.333}} \quad (14)$$

The slip velocity in turbulent flow prevalent in the drill collar annulus can be calculated as:

$$\mathrm{V_{s-turb}} = 113.4 \times \left[0.2 \times \left(\frac{22\ -8.9}{1.5 \times 8.9}\right)\right]^{0.5} = 50.24\ \mathrm{ft/min}$$

Step 2:

Equate the slip velocities to the critical annular velocity and using the relationship below, calculate the pressure drop at the annulus.

Pressure drop in the drill collar-casing annulus is given by:

$$\mathrm{Pl_{dc}} = \frac{\mathrm{L_{dc}\ PV\ V_{crit}}}{60000 \times \left(\mathrm{d_{casing}} - \mathrm{d_{dc}}\right)^2} + \frac{\mathrm{L_{dc}\ YP}}{200 \times \left(\mathrm{d_{casing}} - \mathrm{d_{dc}}\right)} \quad (15)$$

80270H Rev. B [8]

From equation 15, the critical annular velocity, $\mathrm{V_{crit}}$ is equal to the slip velocity in turbulent flow. From the available data presented in Table 1, the pressure drop in turbulent flow prevalent in the drill collar annulus can be calculated as:

$$\mathrm{Pl_{dc}} = \frac{\left(\frac{55.9}{0.3048}\right)\mathrm{ft} \times 6 \times 50.24}{60000 \times (13.375-8)^2} + \frac{\left(\frac{55.9}{0.3048}\right)\mathrm{ft} \times 18}{200 \times (13.375-8)} = 3.103\mathrm{psi}$$

This calculated drill collar annular pressure drop is known as the optimized or critical annular drill collar pressure drop. The actual pressure drop in the drill collar annulus can be calculated using the annular velocity calculated from the mud pump rate using the following relationship:

$$\mathrm{V} = \frac{24.5\ \mathrm{Q}}{\mathrm{d_{casing}^2} - \mathrm{d_{dc}^2}} \quad (16)$$

80270H Rev. B [8]

Where Q = Mud pump rate, gal/min

$$\mathrm{V} = \frac{24.5 \times (760/7.48)\ \mathrm{ft^3/min}}{\left(\frac{13.375}{12}\right)^2 \mathrm{ft^2} - \left(\frac{8}{12}\right)^2 \mathrm{ft^2}} = 3120\mathrm{ft/min}$$

From equation 15, actual annular drill collar pressure drop can be calculated as:

$$\mathrm{Pl_{dc}} = \frac{\left(\frac{55.9}{0.3048}\right)\mathrm{ft} \times 6 \times 3120}{60000 \times (13.375-8)^2} + \frac{\left(\frac{55.9}{0.3048}\right)\mathrm{ft} \times 18}{200 \times (13.375-8)} = 5.051\mathrm{psi}$$

The slip velocity in laminar flow prevalent in the drill pipe annulus can be calculated as a function of the equivalent mud density from equation 14 as:

$$V_{s-lam} = \frac{93.87}{\mu^{0.333}}$$

Total annular pressure loss:

$$Pl_a = Pl_{dp} + Pl_{dc} \tag{17}$$

Pressure drop in the drill pipe annulus is given by:

$$Pl_{dp} = \frac{L_{dp}\ PV\ V_{annular}}{60000 \times \left(d_{casing} - d_{dp}\right)^2} + \frac{L_{dp}\ YP}{200 \times \left(d_{casing} - d_{dp}\right)} \tag{18}$$

80270H Rev. B [8]

Drill pipe annular velocity can be calculated using the following relationship:

$$V = \frac{24.5\ Q}{d_{casing}^2 - d_{dp}^2} \tag{19}$$

$$V = \frac{24.5 \times (760/7.48)\ ft^3/min}{\left(\frac{13.375}{12}\right)^2 ft^2 - \left(\frac{5}{12}\right)^2 ft^2} = 2329.32 ft/min$$

From equation 18, actual annular drill pipe pressure drop can be calculated as:

$$Pl_{dp} = \frac{\left(\frac{318.3}{0.3048}\right) ft \times 6 \times 2329.32}{60000 \times (13.375 - 5)^2} + \frac{\left(\frac{318.3}{0.3048}\right) ft \times 18}{200 \times (13.375 - 5)} = 14.69 psi$$

Actual total annular pressure loss:

$$Pl_a = Pl_{dp} + Pl_{dc} = 14.69 + 5.051 = 19.74\ psi$$

From equation 13, equivalent mud viscosity can be calculated as follows:

$$\mu = \frac{90000 \times 19.74 \times (13.375 - 5)^2}{\left(\frac{318.3 + 55.9}{0.3048}\right) ft \times 2329.32} = 43.575\ cp$$

Substituting the calculated value of equivalent mud viscosity into equation 14 gives the slip velocity in laminar flow prevalent in the drill pipe-casing annulus as:

$$V_{s-lam} = \frac{93.87}{\mu^{0.333}} = 26.71 ft/min$$

Drill pipe annular pressure drop can be calculated at critical annular velocity equal to the slip velocity in laminar flow from equation 18 as shown:

$$Pl_{dp} = \frac{\left(\frac{318.3}{0.3048}\right) ft \times 6 \times 26.71}{60000 \times (13.375 - 5)^2} + \frac{\left(\frac{318.3}{0.3048}\right) ft \times 18}{200 \times (13.375 - 5)} = 11.26\ psi$$

This calculated drill pipe annular pressure drop is known as the optimized or critical annular drill pipe pressure drop.

Step 3:

Optimize the pump pressure by calculating a value of yield point at varying values of plastic viscosity, required to reduce the actual pressure drops at the drill pipe and drill collar annulus to their optimized or critical pressure drop values. From the drill pipe and drill collar pressure drop equations, the plastic viscosity and yield point are the parameters that you can control or alter, while the other parameters are constant and cannot be changed and include the lengths of the drill collar and drill pipe and the diameters of the casing, drill collar and the drill pipe. The annular drill pipe and drill collar optimized pressure drops are therefore mathematical models expressing critical pressure drop in terms of plastic viscosity and yield point as stated below:

To optimize pressure drop at the drill collar annulus, the following mathematical model is used based on the data presented in Table 1:

$$\mathrm{Pl_{dc}} = \frac{\left(\frac{55.9}{0.3048}\right)\mathrm{ft} \times \mathrm{PV} \times 3120}{60000 \times (13.375 - 8)^2} + \frac{\left(\frac{55.9}{0.3048}\right)\mathrm{ft} \times \mathrm{YP}}{200 \times (13.375 - 8)} = 3.103\mathrm{psi}$$

$$0.3301\mathrm{PV} + 0.1706\mathrm{YP} = 3.103\mathrm{psi} \tag{20}$$

To optimize pressure drop at the drill pipe annulus, the following mathematical model is used based on the data presented in Table 1:

$$\mathrm{Pl_{dp}} = \frac{\left(\frac{318.3}{0.3048}\right)\mathrm{ft} \times \mathrm{PV} \times 2329.32}{60000 \times (13.375 - 5)^2} + \frac{\left(\frac{318.3}{0.3048}\right)\mathrm{ft} \times \mathrm{YP}}{200 \times (13.375 - 5)} = 11.26\ \mathrm{psi}$$

$$0.5780\mathrm{PV} + 0.6235\mathrm{YP} = 11.26\mathrm{psi} \tag{21}$$

Equations 20 and 21 give the annular drill collar and drill pipe optimized linear pressure drop mathematical models respectively obtained at actual annular velocity. Different values of plastic viscosity and their corresponding values of yield point which satisfy equations 20 and 21 represent optimum rheological properties of the drilling mud system for hole cleaning in the annulus. However in choosing an optimum value of plastic viscosity and yield point, care should be taken to ensure that drilling problems are avoided. For instance, a low plastic viscosity mud indicates a low solids concentration in the mud and is subject to lost circulation or loss of the liquid phase of the mud and little or no deposition of filter cake which will hinder further fluid loss to the formation.

5. OPTIMIZED HERSCHEL-BULKLEY MODEL FOR DRILL COLLAR ANNULAR HOLE CLEANING

Equation 20 gives the annular drill collar optimized pressure drop mathematical model. From this equation, yield point values are calculated at varying values of plastic viscosity from 1cp to 8cp. This is presented in Table 2. Annular laminar flow behaviour index, annular laminar flow consistency factor and dial readings at 300 rpm and 600 rpm are also presented.

Table 2. Rheological parameters for annular drill collar optimized pressure drop obtained by calculating YP at varying values of PV

Plastic viscosity, PV, cp	Yield point, YP, lb/100ft^2	Dial reading at 300rpm, ϴ300	Dial reading at 300rpm, ϴ600	Laminar flow behaviour index, na	Laminar flow consistency factor, Ka
1	16.25	17.25	18.25	0.20	25.99
2	14.32	16.32	18.32	0.18	26.50
3	12.38	15.38	18.38	0.17	27.06
4	10.45	14.45	18.45	0.16	27.67
5	8.51	13.51	18.51	0.14	28.34
6	6.58	12.58	18.58	0.13	29.06
7	4.64	11.64	18.64	0.11	29.87
8	2.71	10.71	18.71	0.09	30.77

Table 3 shows shear stress-shear rate values calculated using the rheological parameters presented in Table 2 based on calculating YP at varying values of PV (from 1cp to 8cp). Eight Herschel-Bulkley models are generated as a result.

Fig. 1 presents eight (8) Herschel-Bulkley models for the 8 cases of optimized annular drill collar pressure drops presented in Table 3 based on calculating YP at varying values of PV.

From Fig. 1, the yield point is lowest in case 8 (2.71lb/100ft^2), and highest in case 1 (16.25 lb/100ft^2). On the other hand, the plastic viscosity is highest in case 8 (8 cp) and lowest in case 1 (1 cp). This shows that the case 1 Herschel-Bulkley model will exhibit the highest degree of shear thinning characteristics and case 8 Herschel-Bulkley model, the least degree of shear thinning characteristics when compared to the other cases. However a discrepancy occurs when shear thinning characteristics is

Table 3. Shear stress-shear rate values calculated from rheological parameters for optimized annular drill collar pressure drop based on calculating YP at varying values of PV

Case 1		**Case 2**		**Case 3**		**Case 4**	
Shear rate, γ, per sec	**Shear stress, τ , lb/100ft^2**	**Shear rate, γ, per sec**	**Shear stress, τ , lb/100ft^2**	**Shear rate, γ, per sec**	**Shear stress, τ , lb/100ft^2**	**Shear rate, γ, per sec**	**Shear stress, τ , lb/100ft^2**
0	30.67	0	30.81	0	31.25	0	31.71
5.1	36.02	5.1	35.54	5.1	35.71	5.1	35.92
10.2	41.37	10.2	40.27	10.2	40.17	10.2	40.13
170.3	72.62	170.3	66.81	170.3	64.81	170.3	62.95
340.7	83.42	340.7	75.70	340.7	72.92	340.7	70.34
511	90.47	511	81.43	511	78.12	511	75.05
1022	103.92	1022	92.25	1022	87.89	1022	83.85
Case 5		**Case 6**		**Case 7**		**Case 8**	
Shear rate, γ, per sec	**Shear stress, τ , lb/100ft^2**	**Shear rate, γ, per sec**	**Shear stress, τ, lb/100ft^2**	**Shear rate, γ, per sec**	**Shear stress, τ , lb/100ft^2**	**Shear rate, γ, per sec**	**Shear stress, τ , lb/100ft^2**
0	31.98	0	32.53	0	32.91	0	33.35
5.1	35.61	5.1	35.92	5.1	35.74	5.1	35.64
10.2	39.24	10.2	39.31	10.2	38.57	10.2	37.93
170.3	58.18	170.3	56.67	170.3	52.56	170.3	48.86
340.7	64.11	340.7	62.01	340.7	56.73	340.7	52.00
511	67.85	511	65.37	511	59.31	511	53.94
1022	74.77	1022	71.54	1022	64.01	1022	57.41

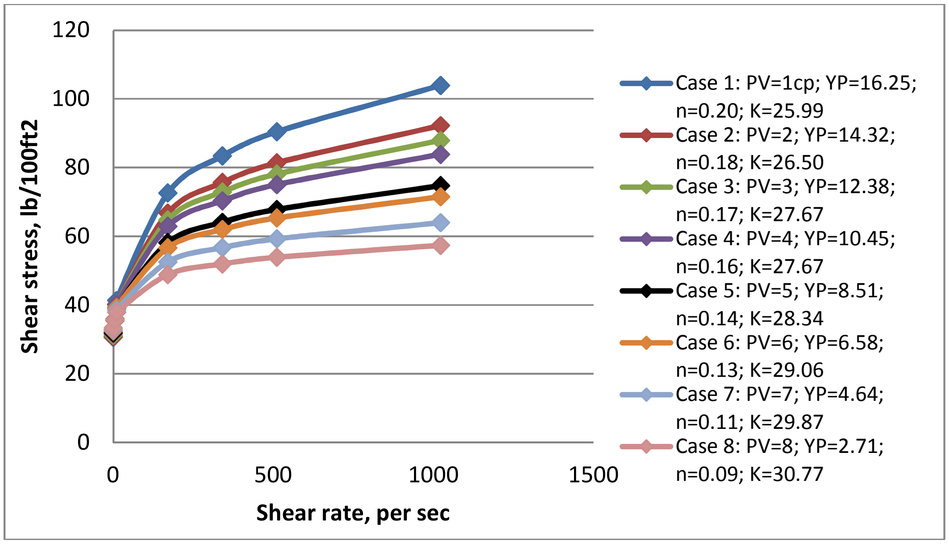

Fig. 1. Optimized Herschel-Bulkley models for optimized annular drill collar pressure drop based on calculating YP at varying values of PV

considered in terms of the annular flow behaviour index, n_a and the annular laminar flow consistency factor, Ka. Fig. 1 shows that case 8 with the least value of n_a and highest value of Ka may be a better optimized model than case 1 with the highest value of n_a and least value of Ka. From Fig. 1, the eight Herschel-Bulkley models were obtained by calculating shear stress values at corresponding values of shear rate which represents the dial readings at 0, 3, 6, 100, 200, 300 and 600 rpm. The values of shear stress calculated are highest in case 1 and least in case 8 for the same values of shear rate. This also shows that case 1 has the highest degree of shear thinning characteristics when compared to the other cases.

6. OPTIMIZED HERSCHEL-BULKLEY MODEL FOR DRILL PIPE ANNULAR HOLE CLEANING

Equation 21 gives the annular drill pipe optimized pressure drop mathematical model. From this equation, yield point values are calculated at varying values of plastic viscosity from 1cp to 8cp. This is presented in Table 4. Annular laminar flow behaviour index, n_a annular laminar flow consistency factor, Ka and dial readings at 300 rpm and 600 rpm are also presented.

Table 4. Rheological parameters for annular drill pipe optimized pressure drop obtained by calculating YP at varying values of PV

Plastic viscosity, PV, cp	**Yield point, YP, lb/100ft^2**	**Dial reading at 300rpm, Ө300**	**Dial reading at 300rpm, Ө600**	**Laminar flow behaviour index, na**	**Laminar flow consistency factor, Ka**
1	17.13	18.13	19.13	0.21	25.53
2	16.21	18.21	20.21	0.21	25.50
3	15.28	18.28	21.28	0.21	25.46
4	14.35	18.35	22.35	0.21	25.42
5	13.42	18.42	23.42	0.21	25.39
6	12.50	18.50	24.50	0.21	25.35
7	11.57	18.57	25.57	0.21	25.32
8	10.64	18.64	26.64	0.21	25.28

Table 5 shows shear stress-shear rate values calculated using the rheological parameters presented in table 4 based on calculating YP at varying values of PV (from 1cp to 8cp). Eight Herschel-Bulkley models are generated as a result.

Table 5. Shear stress-shear rate values calculated from rheological parameters for optimized annular drill pipe pressure drop based on calculating YP at varying values of PV

Case 1		**Case 2**		**Case 3**		**Case 4**	
Shear rate, γ, per sec	**Shear stress, τ, lb/100ft^2**	**Shear rate, γ, per sec**	**Shear stress, τ, lb/100ft^2**	**Shear rate, γ, per sec**	**Shear stress, τ, lb/100ft^2**	**Shear rate, γ, per sec**	**Shear stress, τ, lb/100ft^2**
0	30.27	0	30.29	0	30.24	0	30.21
5.11	35.93	5.11	35.92	5.11	35.86	5.11	35.81
10.22	41.59	10.22	41.55	10.22	41.48	10.22	41.41
170.3	75.09	170.3	75.01	170.3	74.89	170.3	74.77
340.7	86.87	340.7	86.76	340.7	86.63	340.7	86.49
511	94.58	511	94.47	511	94.32	511	94.18
1022	109.40	1022	109.28	1022	109.10	1022	108.93
Case 5		**Case 6**		**Case 7**		**Case 8**	
Shear rate, γ, per sec	**Shear stress, τ, lb/100ft^2**	**Shear rate, γ, per sec**	**Shear stress, τ, lb/100ft^2**	**Shear rate, γ, per sec**	**Shear stress, τ, lb/100ft^2**	**Shear rate, γ, per sec**	**Shear stress, τ, lb/100ft^2**
0	30.15	0	30.12	0	30.07	0	30.03
5.11	35.76	5.11	35.71	5.11	35.66	5.11	35.61
10.22	41.37	10.22	41.30	10.22	41.25	10.22	41.19
170.3	74.68	170.3	74.56	170.3	74.48	170.3	74.36
340.7	86.39	340.7	86.25	340.7	86.15	340.7	86.01
511	94.07	511	93.92	511	93.81	511	93.66
1022	108.80	1022	108.63	1022	108.50	1022	108.33

Fig. 2 presents eight (8) Herschel-Bulkley models for the 8 cases of optimized annular drill pipe pressure drops presented in Table 5 based on calculating YP at varying values of PV.

From Fig. 2, the yield point is lowest in case 8 ($10.64 lb/100ft^2$), and highest in case 1 ($17.13 lb/100ft^2$). On the other hand, the plastic viscosity is highest in case 8 (8cp) and lowest in case 1 (1cp). This shows that the case 1 Herschel-Bulkley model will exhibit the highest degree of shear thinning characteristics and case 8 Herschel-Bulkley model, the least degree of shear thinning characteristics when compared to the other cases. When shear thinning characteristics is considered in terms of the annular laminar flow behaviour index, n_a and the annular laminar flow consistency factor, Ka, all the eight model cases analyzed have equal values of n_a and approximately equal values of Ka. This is evident from Fig. 2 where all the eight optimized Herschel-Bulkley models are seen to overlap signifying approximately equal values of shear stress at corresponding values of shear rate. From Fig. 2, all the eight cases presented have comparable shear thinning characteristics when analyzed in terms of the annular laminar flow behaviour index and the annular laminar flow consistency factor. The laminar flow regime existent in the drill pipe annulus is the reason for the overlap of the rheological models in Fig. 2. In the drill pipe annulus, the drilling mud deforms at a low shear rate. The degree of frictional drag defined by the drilling mud shear stress will be the same for the eight Herschel-Bulkley models since they were generated assuming equal critical drill pipe annular pressure drop. On the other hand, turbulent flow is prevalent in the drill collar annulus and is the reason for the disparity that exists within the eight Herschel-Bulkley models for annular drill collar hole cleaning as shown in Fig. 1. The drilling mud deforms at a higher shear rate in turbulent flow and the degree of frictional drag will vary across the eight Herschel-Bulkley models even though they were generated at the same critical drill collar annular pressure drop.

7. OPTIMIZED HERSCHEL-BULKLEY MODEL FOR COMBINED DRILL COLLAR AND DRILL PIPE ANNULAR HOLE CLEANING

The combined drill collar and drill pipe annular hole cleaning is designed on the basis of the yield point and plastic viscosity values obtained by solving simultaneously, the set of annular drill pipe and drill collar optimized pressure drop equations 20 and 21 respectively. Here, only one set of rheological parameters is defined in terms of YP, PV, ϴ300, ϴ600, n and K values.

Solve simultaneously these systems of mathematical models by making PV the subject of formula in equation 20.

$$\mathrm{PV} = \frac{3.103 - 0.1706\mathrm{YP}}{0.3301} \qquad (22)$$

Substitute the value of PV in equation 22 into equation 21 gives:

$$0.5780\left(\frac{3.103 - 0.1706\mathrm{YP}}{0.3301}\right) + 0.6235\mathrm{YP} = 11.26\mathrm{psi} \qquad (23)$$

From equation 22 and 23,

$$\mathrm{PV} = 0.13\mathrm{cp}; \;\; \mathrm{YP} = 17.94\ \mathrm{lb/100ft^2}$$

Table 6 shows values of YP, PV, ϴ300, ϴ600, n and K before and after mud pump pressure optimization, and were calculated based on the rheological and hydraulic data presented in Table 1.

Herschel-Bulkley Model for the combined annular drill collar and drill pipe optimized and non-optimized pressure drop is presented in Table 7.

Fig. 3 shows the Herschel-Bulkley rheogram for the combined annular drill collar and drill pipe optimized pressure drop.

The non-optimized Herschel-Bulkley model is obtained at actual annular pressure drop using the rheological data presented in Table 1. The optimized Herschel-Bulkley model is obtained at critical annular pressure drop by calculating shear stress values at corresponding values of shear rate which represents the dial readings at 0, 3, 6, 100, 200, 300 and 600 rpm (or 0, 5.11, 10.22, 170.3, 340.7, 511 and 1022 sec^{-1} respectively) using the Herschel-Bulkley equation given below:

$$\tau = \mathrm{K}\gamma^{n} + \tau_y \qquad (24)$$

The yield stress which represents the shear stress reading at zero shear rate is given as:

$$\tau_y = 2\theta_3 - \theta_6 \qquad (25)$$

From Fig. 3, the values of shear stress calculated are higher in the optimized model than in the non-optimized model for the same values of shear rate. This shows that the optimized model has a better shear thinning characteristics than the non-optimized model. The optimized model has the following advantages over the non-optimized model:

1. The mud pump pressure is optimized by reduction in annular pressure.
2. The rheological parameters are calculated and the Herschel-Bulkley model designed on the basis of the annular velocity and critical pressure drop.

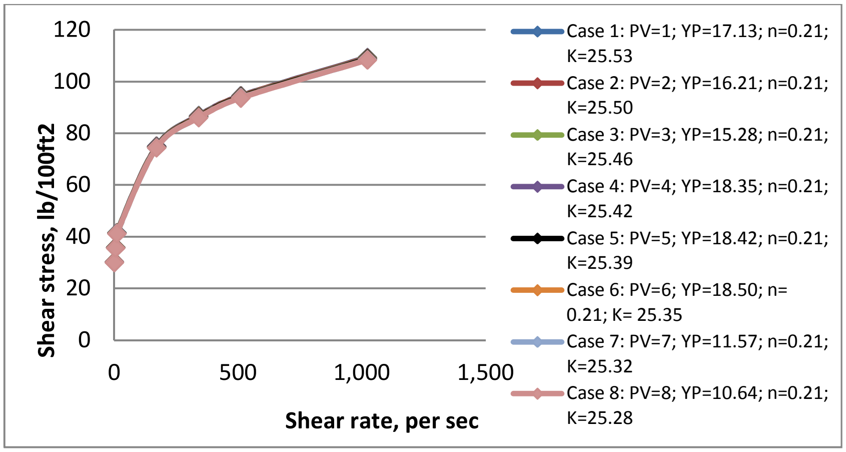

Fig. 2. Optimized Herschel-Bulkley models for annular drill pipe pressure drop based on calculating YP at varying values of PV

Table 6. Rheological parameters for combined annular drill pipe and drill collar optimized and non-optimized pressure drop

Herschel Buckley model	Yield Point, YP, lb/100ft^2	Plastic viscosity, PV, cp	Dial reading at 300rpm, Ɵ300	Dial reading at 600rpm, Ɵ600	Laminar flow behaviour index, na	Laminar flow consistency factor, Ka
Optimized	17.94	0.13	18.07	18.20	0.21	25.56
Non-optimized	18	6	24	30	0.27	22.77

Table 7. Herschel-Bulkley model for combined annular drill pipe and drill collar optimized and non-optimized pressure drop

Optimized model		Non-optimized model	
Shear rate, γ	**Shear stress, τ , lb/100ft^2**	**Shear rate, γ**	**Shear stress, τ , lb/100ft^2**
0	30.27	0	6
5.11	35.76	5.11	7
10.22	41.24	10.22	8
170.3	73.64	170.3	16
340.7	84.94	340.7	19
511	92.34	511	24
1022	106.51	1022	30

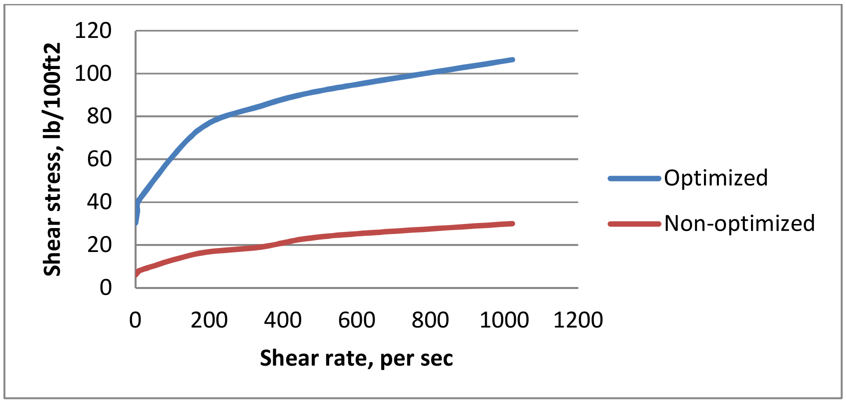

Fig. 3. Herschel-Bulkley rheogram for the combined annular drill collar and drill pipe optimized pressure drop

8. CONCLUSION

The following conclusions can be made from the analysis presented in this paper:

1. Mud Rheology is the most important factor that impacts hole cleaning.
2. Shear thinning is the property of the drilling mud required for an efficient hole cleaning in the annulus.
3. The higher the value of the yield point, YP and annular laminar flow consistency factor, Ka the higher the degree of shear thinning of the mud. Similarly, the lower the value of plastic viscosity, PV and the lower the value of the annular laminar flow behaviour index, na, the higher the degree of shear thinning of the mud.
4. In either laminar or turbulent flow, critical annular velocity is equal to the slip velocity of cuttings.
5. Optimized or critical pressure loss is calculated at critical annular velocity.
6. Optimum rheological mud properties as well as the optimum Herschel-Bulkley model, are obtained at critical annular pressure drop and actual annular velocity.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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