Kpea-ue Marvin Lezor

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Department of Petroleum and Gas Engineering
University of Port Harcourt
Email: marvinlezor@yahoo.com

The link to this publication is https://ajoeer.org.ng/otn/ajoeer/qtr-1/2020/05

ISSN: 2635-2974

Evaluating the Effect of Mud Rheology and Cuttings Size on Cuttings Transportation in Vertical Wells

Chukwu A. Godwin, Kpea-ue Marvin Lezor, Kinate Bright
Department of Petroleum and Gas Engineering
University of Port Harcourt
Email: marvinlezor@yahoo.com
[Date received: Dec 2019. Date accepted: Jan 2020]

Abstract

As drilling optimization becomes the major concern of the drilling engineer and the mud specialist, there is therefore need to properly evaluate key success factors that ultimately affects the success of drilling operations. This research work examined the effects of fluid rheology and cuttings size on cuttings transportation in vertical wells. To achieve that, an experiment was conducted on two samples of fresh oil-based mud (A and B) of different rheology and two drilled cuttings sample (A and B) of sizes 400µm and 1000µm obtained from Anieze North field after sieve analysis. The drilled cuttings samples(A and B) were comingled with the mud(A and B) and their rheology (viscosity, density, plastic viscosity, yield point and gel strength) and cuttings transport parameters (slip velocity, transport velocity, transport ratio and transport efficiency) were checked at different temperatures. The cuttings transport parameters generated with the test models (Moore, Chien et al, and Zeidler) reveal that drilled cuttings of smaller size are easily transported than those of larger size. It was also observed that temperature has remarkable effects on rheology and slip velocity. Hence, slip velocity increases with temperature, while rheological values decrease with temperature. As a recommendation arising from the results of this investigation, a lower cuttings size should be ensured in a low viscous fluid for an efficient hole-cleaning. Apart from the aforementioned factors for efficient transportation of drilled cuttings, drilling bit configuration which is major determinant of the size of cuttings should be properly examined before selection for any drilling operation.

Keywords: Cuttings Size, Cuttings Transport, Mud Rheology, Slip Velocity, Temperature

1. INTRODUCTION

A critical look into some research works regarding cutting transportation, fluid viscosity, cutting shape and size, cutting concentration, yield point, gel strength, etc., demonstrate the efficiency of cutting transportation depends on the properties (rheology) of the drilling fluid and cuttings mesh size. Cuttings removal and wellbore challenges presents the mud engineer with the major challenges in both vertical and deviated wells. In drilling operations, cutting transport is a major factor that determines the success of the operation. As viewed by

Pilelivari *et al* (1991), in their presentation on the overview of the development in cutting transportation over the years, they focused on pioneering experimental studies performed between 1986 and 1991. At the end of their review, a conclusive guideline was presented for efficient hole cleaning. Belavadi and Chukwu (1994) in their quest to understand the parameters that affects cuttings transportation constructed a simulation and observed cuttings transport in the annulus. A graphical correlation of a dimensionless form versus vertical ratio of the data collected from the simulation was presented. It was deduced from the analysis that density difference ratio between the drilling fluid and drilled cuttings affects cuttings transport majorly. They came to the conclusion that increase in the fluid flow rate would increase cuttings transport performance in the annulus, and at low drilling fluid density, the above effect is neglected when cuttings have large diameter. They also concluded that small size cuttings transport can be increase with high drilling fluid density and drill pipe rotation.

With a focus on the understanding of the phenomena involved in eroding the cutting been deposited on the lower side of the annular suction, Martins and Costapinto (1996) showed in their experimental program, a set correlation base on the results for the prediction of bed height and critical flow rate during the correlation of a horizontal well. It was observed from their experimental result that fluid yield point (YP) was significant only in the erosion of eccentric annuli. An additional research was required to ascertain more accurate interpretation of fluid rheological effects.

Sanchez et al (1997) in their research itemized some of the factors that affect hole-cleaning as fluid viscosity, drilled cuttings features, drill string rotation, ROP, annular drilling fluid velocity and hole inclination. They also observed that there exist limitation of all these factors affecting hole cleaning. They concluded that careful planning and consideration of all those variables were needful, and that hole cleaning of a deviated well was a major challenge hence, the need to address the issue in the research and methodology before the presentation of a universal hole cleaning solution.

Yu et al (2004) trying to be outstanding in proffering solution to inefficient lifting of cuttings by drilling fluid used chemical surfactant in addition to air bubble added to cuttings at the surface to improve cutting transport capacity in horizontal wellbore. The aim of their experiment was to ascertain the effects of chemical surfactant on the attachment of air bubble to cuttings transport. Their study revealed that the use of some chemical surfactant could increase the strength of the attachment between the air bubble and the cuttings particles. It concluded that this method could improve cuttings transport in horizontal wells.

It is imperative to note that deviating a well horizontally or directionally while drilling is always a solution to bypass the obstructions on the drilling pathway to reach the desired or targeted zone for the economic exploitation of oil and gas reserves but the importance of cleaning a vertical well cannot be overemphasized (Cameron, 2001; Ali *et al*., 2012).

Tie *et al* (2014) affirmed that to determine and overcome hole-cleaning challenges in a drilling operation, hole cleaning detect method should be deployed. Detect methods such as flow rate control method, chemical method and mechanical methods are used to combat hole cleaning problems in horizontal and vertical well drilling. During the process of drilling, cutting beds are often formed at more than 30o inclination. The beds so formed are prone to slide along an inclination of 30o and 60o in the wellbore thereby causing stuck pipe, reduce weight on bit that results in reduced ROP, outrageous drill pipe wear, extra cost for special mud additives and transient hole blockage heading to lost circulation.

Several methods such as flow rate method, fluid chemical composition control method, mud additives control method and mechanical control method have proved efficient in removing drill cuttings from the well. Savin (1985) showed that the unbearable effects of high flow velocities can be overcome by injecting in the the annulus, a slug or slugs in their series with a shear thickening time. According to Zhang et al (1999), hole cleaning are closely achieved for fluid flow at a velocity of 32-35liters/second and 60liters/second in a hard formation wellbore. In Tie et al (2014) studies, it is shown that increase in fluid velocity has been a well-known solution to cutting transportation since it is capable of decreasing cutting concentration and height of cutting bed accumulation at different angles of a horizontal well where cuttings are either formed or settled.

Okrajni et al (1986) in their experiment disclosed that a higher fluid yield pointertion in his model that (YP) and YP/PV values provides better cuttings transport in laminar flow scenario whereas in turbulent flow scenarios, cuttings transport is not affected by mud rheology. In Naraghi (1998) work, he made a strong assertion that if phosphate and sulphate is pumped down a drill string as a slug, it will coat the cutting that accumulates in the well. Such will enable them to be removed from the wellbore alongside, the drilling fluid. Ali et al (2012) concluded in their research that increasing the plastic viscosity of the drilling fluid is one of the solutions to ensure an effective hole-cleaning operation. The amount of recovered cuttings is remarkably enhanced when plastic viscosity is increased. They also disclosed that while increasing the viscosity of a mud, care must be taken to ensure the viscosity is not excessively increased to avert it adverse effects on the expected overall result. However, in a model developed by Tie *et al* (2014), they disclosed a procedure that allows a low viscosity fluid with drill cuttings suspension capable of a high viscous fluid which is easily pumpable.

Several fluid additives have been introduced over the years to control cutting beds formation. As recorded by Wang *et al* (2013), the various control methods introduced to control cuttings bed formation has effects on fluid rheology. Rheological properties such as YP/PV, n, and gel strength are properties enhance fluid transport ability of drilled cuttings. Fortunately or unfortunately as the case might be, some of the methods are not efficient enough to stop cuttings bed formation. Incidentally, Wang *et.al (*2013), disclosed that fibre sweep can be used for effective borehole cleaning and reduction in cuttings bed formation in both vertical and horizontal wells.

In certain cases, cuttings removal tools (CRT) have been deployed as mechanical control equipment with certain limitations

2. RESEARCH METHODOLOGY

In this study, three drill cuttings transport efficiency models (Moore, Chien and Zeidler models) were incorporated with an experimental laboratory results (gotten at the Department of Petroleum Engineering Laboratory, University of Port Harcourt, Nigeria) and a commercial Crystal Ball ® simulator via Monte Carlo Simulation technique. Sensitivity runs were made with the simulator in order to determine the effects of optimizing parameters for continuous and effective drill cuttings transportation out of the hole.

2.1 Experimental Sample Specification

This research work analyzes two unique samples of drilling mud and drill cuttings. These samples were formulated to represent different test scenarios of different mud mixtures. The test samples are briefly described below:

- Mud Sample (A): Freshly prepared OBM
- Mud Sample (B): Freshly prepared OBM

- Drill Cuttings Sample (A): A 400µm drill cuttings from Anieze North Field, Niger Delta
- Drill Cuttings Sample (B): A 1000µm drill cuttings from Anieze North Field, Niger Delta

Special mud mixtures were formulated from the above samples by adding about 10% by weight of the drill cuttings samples in order to generate the following test scenarios

- Mud Sample (A) + Drill Cuttings Sample (A)
- Mud Sample (A) + Drill Cuttings Sample (B)
- Mud Sample (B) + Drill Cuttings Sample (A)
- Mud Sample (B) + Drill Cuttings Sample (B)

2.2 The Cuttings Transport Efficiency Models

- **The Moore's Model**

For the calculation of slip velocity as demonstrated by Moore (1974), the apparent viscosity of the fluid was obtained by equating the annular frictional pressure loss equation for the power law and Newtonian fluid models.

By definition, the apparent viscosity (which constitute a key parameter in mud rheological models) is defined as follows

$$\mu_a = \frac{K}{144}\left(\frac{d_2 - d_1}{V_a}\right)^{1-n}\left[\frac{2 + \frac{1}{n}}{0.0208}\right]^n \qquad (1)$$

Reynolds Number is calculated using apparent viscosity as follows:

$$NR_e = \frac{928\rho_f V_{sl} d_s}{\mu_a} \qquad (2)$$

For Reynolds number greater than 300 (fully turbulent), the slip velocity can be calculated as:

$$V_{slip} = 1.54\sqrt{ds\frac{\rho_s - \rho_f}{\mu_a}} \qquad (3)$$

For Reynolds number of 3 or less (fully laminar), when flow is considered to be laminar with straight line plots of frictional factor given as

$$F = \frac{40}{NR_e} \quad (4)$$

The slip velocity equation becomes:

$$V_{slip} = 82.87 \frac{d_s^{\,2}}{\mu_a} \left(\rho_s - \rho_f\right) \quad (5)$$

For intermediate Reynolds numbers of greater than 3 and less than 300, the dash line approximation for friction factor is given by

$$F = \frac{22}{\sqrt{NR_e}} \quad (6)$$

For the above relation, the equation for slip velocity becomes

$$V_{slip} = \frac{2.90ds \left(\rho_s - \rho_f\right)}{\rho_f 0.333 \quad \mu_a 0.333} \quad (7)$$

Where

$$n = 3.22 \log\left(\frac{R600}{R300}\right) \quad and \quad K = \frac{510\left(R300\right)}{511^n} \quad (8)$$

The Transport ratio (F_T) is defined as follows:

$$F_T = \frac{\overline{V_T}}{\overline{V}_a} = 1 - \frac{\overline{V}_{slip}}{V_a} \quad (9)$$

Transport efficiency (F_{Te})

$$F_{Te} = \frac{\overline{V_T}}{\overline{V}_a} \text{ x } 100$$

(10)

- **The Chein et al Model**

For settling velocity in a rotary drilling operation, two empirical correlations are presented, one for determination of the settling velocity and the other a simplified version for the turbulent slip regime. For mixtures of water and bentonite, Chein (2012) proposed that the plastic viscosity can be used as apparent viscosity, while for polymer type drilling fluids; the apparent viscosity is calculated as thus:

$$\mu_a = \mu_\rho + 300 \frac{T_y \ d_s}{V_a} \quad (11)$$

Where μ_a = apparent viscosity, μ_p= plastic viscosity (pv), T_y = yield stress (ys) or yield point (yp) and d_s = diameter of drill string.

Settling velocity or slip velocity is the velocity at which the solid particles sink down through liquid. The empirical equation tried to correlate factors such as cutting size, cutting density, mud weight, and viscosity of the mud to settling viscosity

The empirical equation for settling velocity, V_{slip} is given as

$$V_{slip} = 1.44\sqrt{d_c \ \frac{\rho_c - \rho_f}{\rho_f}}, \quad NR_e > 100 \quad (12)$$

or

$$V_{slip} = 0.0075 \left(\frac{\mu_a}{\rho_f \ d_c}\right)\left[\sqrt{\frac{36800 d_c}{\left(\frac{\mu_a}{\rho_f \ d_c}\right)^2}\left(\frac{d_c - \rho_f}{\rho_f}\right) + 1} - 1\right], \quad NR_e \leq 100 \quad (13)$$

Where V_{slip}= slip velocity, μ_a= apparent viscosity, ρ_f = density of fluid, d_c= diameter of cuttings,

All correlations are given in field units and ρ_c is cutting density.

Transport ratio (F_T) is defined as follows:

$$F_T = \frac{\overline{V_T}}{\overline{V}_a} = 1 - \frac{\overline{V}_{slip}}{V_a} \quad (14)$$

Transport efficiency (F_{Te})

$$F_{Te} = \frac{\overline{V_T}}{\overline{V_a}} \times 100$$

(15)

- **Zeidler Slip Velocity Correlation**

Zeidler (1972) performed cuttings transport experimental study and generated a slip velocity correlation equation. The study shows that the pipe rotation and drilling muds produces changes in recovery fractions. From the study, the following relations were obtained to determine the settling velocity (V_s) of the drilled particles in a Newtonian fluid.

$2 \leq NR_{eP} \leq 15$

$$V_s = 13.42 \frac{(\rho_s - \rho_l)^{0.782}}{\rho_l 0.218} \frac{d_{eg}^{1.35}}{\mu^{0.364}}$$

(23)

$15 \leq NR_{eP} \leq 80$

$$V_s = 13.88 \frac{(\rho_s - \rho_l)^{0.612}}{\rho_l 0.388} \frac{d_{eg}^{0..835}}{\mu^{0224}}$$

(24)

$80 \leq NR_{eP} \leq 1500$

$$V_s = 17.88 \frac{(\rho_s - \rho_l)^{0.516}}{\rho_l 0.48} \frac{d_{eg}^{0.548}}{\mu^{0.032}}$$

(25)

Where

$V_{s=}$ slip velocity, ρ_s = density of solid, ρ_l = density of fluid, d_{eg} = equivalent diameter, $NR_{eP\,=}$ Reynolds Number, μ = apparent viscosity.

The particle velocity relative to the surface called the transport velocity (V_T) is given as

$$V_T = \overline{V_a} - \overline{V_{slip}}$$

(26)

Transport ratio (F_T) is defined as follows:

$$F_T = \frac{\overline{V_T}}{\overline{V}_a} = 1 - \frac{\overline{V}_{slip}}{V_a} \quad (27)$$

Transport efficiency (F_{Te})

$$F_{Te} = \frac{\overline{V_T}}{\overline{V}_a} \times 100 \quad (28)$$

In the Zeidler's relation, all values are in *cgs* units. From this relation, the dependence of settling velocity on viscosity is seen to decrease with increasing Reynolds Numbers. This indicates that the form drags becomes more predominant and the viscous drag becomes less significant with increasing Reynolds numbers.

In the above models, the model input mud flow rate (340gpm) were calculated from field data based on Bourgoyne, (1991) minimum and maximum flow rate equations.

3. RESULTS AND DISCUSSION

The various fluid sampling systems used in this work is presented in Tables (1-2) for the different cuttings transport models. The behavior of the various transport parameters at different temperature ranges is clearly shown for each test scenario and cuttings transport model.

3.1 The Variation of Transport Parameters with Mud Rheology

This section presents the variation of transport properties with certain fluid rheological parameters. Parameters studied include the Plastic Viscosity, Yield point and Gel strength. These properties impact the "transportability" of a fluid system in distinct manners and to varying degrees. This is clearly visible in the Fig 1-18 below.

Table 1: Rheological and Transport Parameters of Fluid Systems 1 and 2

Models	**Cuttings A + Mud A**	**Cuttings B + Mud A**

Moore

Parameter	80°F	100°F	120°F	150°F	180°F
V_T, ft/s	3.325435	3.325435	3.325435	3.325435	3.32543
Pf	10.4	10.4	10.4	10.4	10.
N	0.935326	0.940292	0.949573	0.956884	0.97246
K	171.7949	162.2117	140.7878	112.3116	63.989
µa, cp	127.5685	123.2541	111.6722	92.15139	56.4296
Vslip, ft/s	0.001713	0.001773	0.001957	0.002371	0.00387
Nre	0.002041	0.002186	0.002663	0.003911	0.01043
Ft	0.999485	0.999467	0.999412	0.999287	0.99883
Fte, %	99.94849	99.94668	99.94115	99.92869	99.8835

Parameter	80°F	100°F	120°F	150°F	180°F
V_T, ft/s	3.325435	3.325435	3.325435	3.325435	3.325435
Pf	10.3	10.3	10.3	10.3	10.3
N	0.963942	0.971421	0.972468	0.974911	0.977737
K	179.9589	155.0584	127.9796	103.8698	76.82832
µa, cp	152.5583	136.0782	112.8593	92.63925	69.42305
Vslip, ft/s	0.008605	0.009647	0.011632	0.014171	0.01891
Nre	0.021226	0.026679	0.038785	0.057564	0.102503
Ft	0.997412	0.997099	0.996502	0.995739	0.994314
Fte, %	99.74123	99.7099	99.65021	99.57386	99.43136

Chien

Parameter	80°F	100°F	120°F	150°F	180°F
µa, cp	105	103	96	81	5
V_T, ft/s	3.325435	3.325435	3.325435	3.325435	3.32543
Pf	10.4	10.4	10.4	10.4	10.
Vslip, ft/s	0.003465	0.003532	0.003789	0.00449	0.00698
Nre	0.005015	0.005212	0.005999	0.008425	0.02042
Ft	0.998958	0.998938	0.998861	0.99865	0.99789
Fte, %	99.89582	99.89379	99.88606	99.86498	99.7898

Parameter	80°F	100°F	120°F	150°F	180°F
µa, cp	137	125	104	86	65
V_T, ft/s	3.325435	3.325435	3.325435	3.325435	3.325435
Pf	10.3	10.3	10.3	10.3	10.3
Vslip, ft/s	0.015907	0.017423	0.020907	0.02522	0.033175
Nre	0.043694	0.052453	0.075649	0.110357	0.192064
Ft	0.995217	0.994761	0.993713	0.992416	0.990024
Fte, %	99.52165	99.47606	99.37131	99.2416	99.00239

Zeidler

Parameter	80°F	100°F	120°F	150°F	180°F
Pf	10.4	10.4	10.4	10.4	10.4
µa, cp	127.5685	123.2541	111.6722	92.15139	56.42964
V_T, ft/s	3.325435	3.325435	3.325435	3.325435	3.325435
Vslip, ft/s	0.032259	0.032666	0.033861	0.036314	0.043411
Nre	0.038434	0.040281	0.046085	0.059893	0.116923
Ft	0.990299	0.990177	0.989818	0.98908	0.986946
Fte, %	99.02992	99.01769	98.98177	98.90801	98.69458

Parameter	80°F	100°F	120°F	150°F	180°F
Pf	10.3	10.3	10.3	10.3	10.3
µa, cp	152.5583	136.0782	112.8593	92.63925	69.42305
V_T, ft/s	3.325435	3.325435	3.325435	3.325435	3.325435
Vslip, ft/s	0.101171	0.10547	0.112903	0.121315	0.134747
Nre	0.249558	0.291669	0.376459	0.492799	0.730412
Ft	0.969577	0.968284	0.966049	0.963519	0.95948
Fte, %	96.95766	96.82839	96.60488	96.35191	95.94798

Table 2: Rheological and Transport Parameters of Fluid Systems 3 and 4

Models	Cuttings A + Mud B	Cuttings B + Mud B

Moore

Cuttings A + Mud B

Parameter	80°F	100°F	120°F	150°F	180°F
V_T, ft/s	3.325435	3.325435	3.325435	3.325435	3.325435
Pf	9.8	9.8	9.8	9.8	9.8
N	0.927908	0.929071	0.946208	0.949695	0.968411
K	145.5084	130.477	96.31379	80.58371	57.12211
µa, cp	104.3997	94.12066	75.21505	63.95495	49.43652
Vslip, ft/s	0.002211	0.002453	0.003069	0.00361	0.00467
Nre	0.003034	0.003732	0.005844	0.008084	0.013529
Ft	0.999335	0.999262	0.999077	0.998914	0.998596
Fte, %	99.9335	99.92624	99.9077	99.89145	99.85957

Cuttings B + Mud B

Parameter	80°F	100°F	120°F	150°F	180°F
V_T, ft/s	3.325435	3.325435	3.325435	3.325435	3.325435
Pf	9.6	9.6	9.6	9.6	9.6
N	0.950538	0.954217	0.955051	0.948823	0.967017
K	122.2798	107.5561	87.18332	79.65011	55.16884
µa, cp	97.42632	87.16678	70.92954	62.95919	47.43913
Vslip, ft/s	0.014397	0.016092	0.019776	0.022279	0.029568
Nre	0.051832	0.064751	0.09779	0.124116	0.218612
Ft	0.995671	0.995161	0.994053	0.9933	0.991108
Fte, %	99.56705	99.51609	99.40532	99.33003	99.11085

Chien

Parameter	80°F	100°F	120°F	150°F	180°F
μa, cp	84	76	64	55	45
V_T, ft/s	3.325435	3.325435	3.325435	3.325435	3.325435
Pf	9.8	9.8	9.8	9.8	9.8
Vslip, ft/s	0.004574	0.005055	0.006001	0.006981	0.008527
Nre	0.007799	0.009526	0.013429	0.018178	0.027137
Ft	0.998624	0.99848	0.998195	0.997901	0.997436
Fte, %	99.86245	99.84799	99.81954	99.79008	99.74359

Parameter	80°F	100°F	120°F	150°F	180°F
μa, cp	84	76	62	54	43
V_T, ft/s	3.325435	3.325435	3.325435	3.325435	3.325435
Pf	9.6	9.6	9.6	9.6	9.6
Vslip, ft/s	0.02758	0.030428	0.037115	0.042417	0.052695
Nre	0.115158	0.140425	0.209964	0.275506	0.429819
Ft	0.991706	0.99085	0.988839	0.987245	0.984154
Fte, %	99.17065	99.085	98.8839	98.72447	98.4154

Zeidler

Parameter	80°F	100°F	120°F	150°F	180°F
Pf	9.8	9.8	9.8	9.8	9.8
μa, cp	104.3997	94.12066	75.21505	63.95495	49.43652
V_T, ft/s	3.325435	3.325435	3.325435	3.325435	3.325435
Vslip, ft/s	0.036695	0.038106	0.041347	0.043861	0.048171
Nre	0.05034	0.057984	0.078729	0.098221	0.139552
Ft	0.988965	0.988541	0.987567	0.98681	0.985514
Fte, %	98.89653	98.8541	98.75665	98.68105	98.55145

Parameter	80°F	100°F	120°F	150°F	180°F
Pf	9.6	9.6	9.6	9.6	9.6
μa, cp	97.42632	87.16678	70.92954	62.95919	47.43913
V_T, ft/s	3.325435	3.325435	3.325435	3.325435	3.325435
Vslip, ft/s	0.127383	0.132648	0.142984	0.149325	0.16553
Nre	0.458586	0.533748	0.707045	0.831876	1.22384
Ft	0.961694	0.960111	0.957003	0.955096	0.950223
Fte, %	96.16943	96.0111	95.70028	95.50962	95.02232

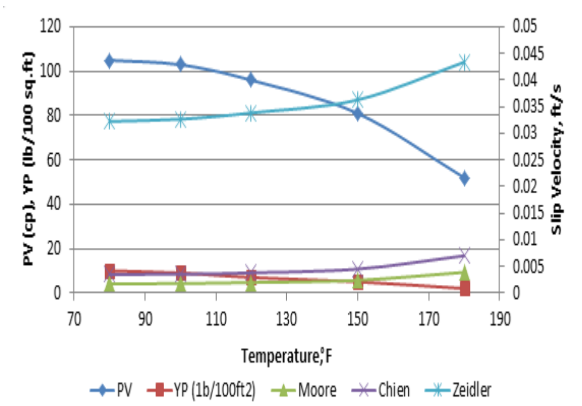


Fig 1: Variation of Plastic viscosity, Yield Point and Slip Velocity with Temperature for system of Mud A and Cuttings A

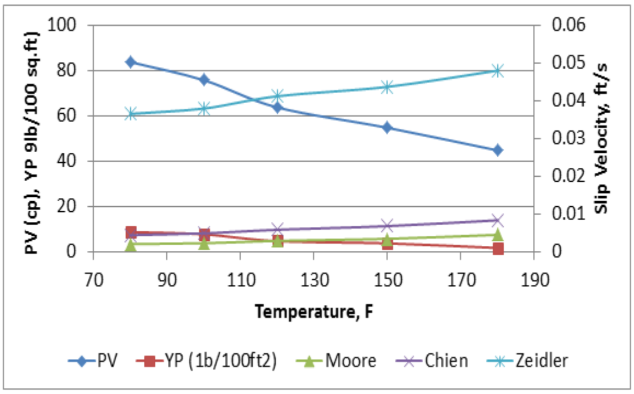
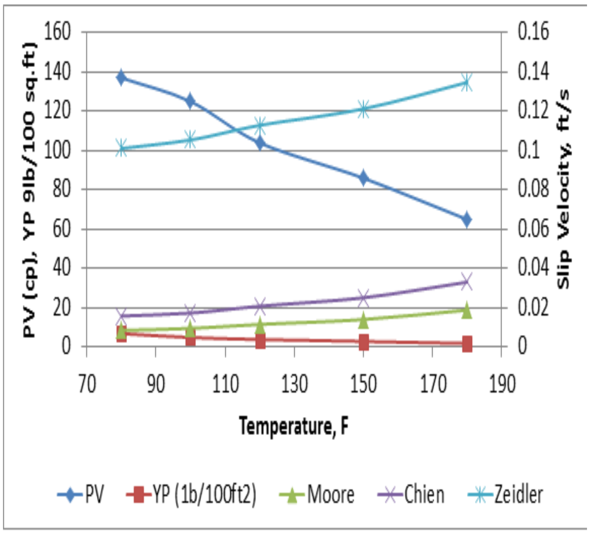


Fig 2: Variation of Plastic viscosity, Yield Point and Slip Velocity with Temperature for system of Mud B and Cuttings A



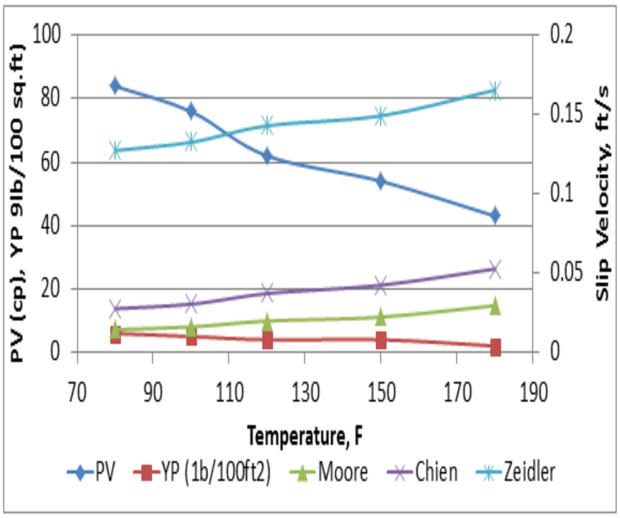


Fig 3: Variation of Plastic viscosity, Yield

Fig 4: Variation of Plastic viscosity, Yield Point

Point and Slip Velocity with Temperature for system of Mud A and Cuttings B

and Slip Velocity with Temperature for system of Mud B and Cuttings B

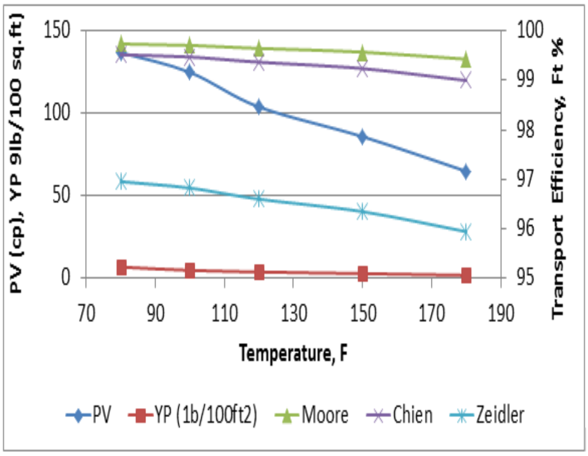


Fig 5: Variation of Plastic viscosity, Yield Point and Transport Efficiency with Temperature for system of Mud A and Cuttings B

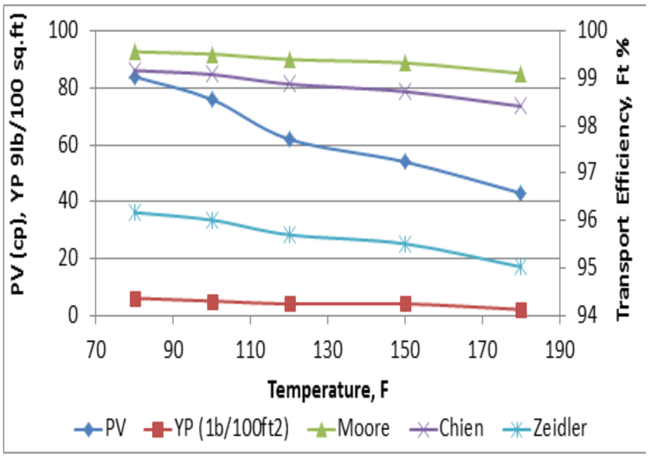


Fig 6: Variation of Plastic viscosity, Yield Point and Transport Efficiency with Temperature for system of Mud B and Cuttings B

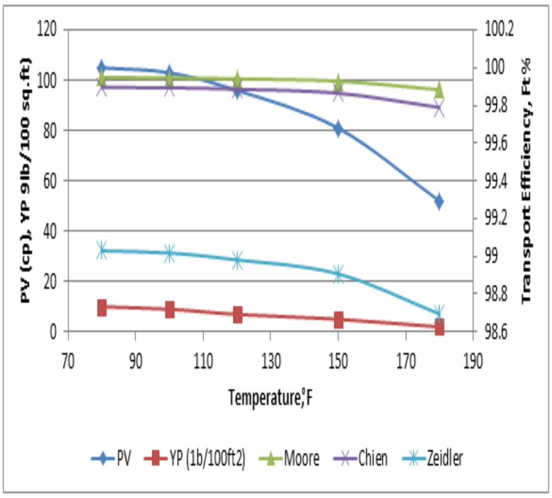


Fig 7: Variation of Plastic viscosity, Yield Point and Transport Efficiency with Temperature for system of Mud A and Cuttings B

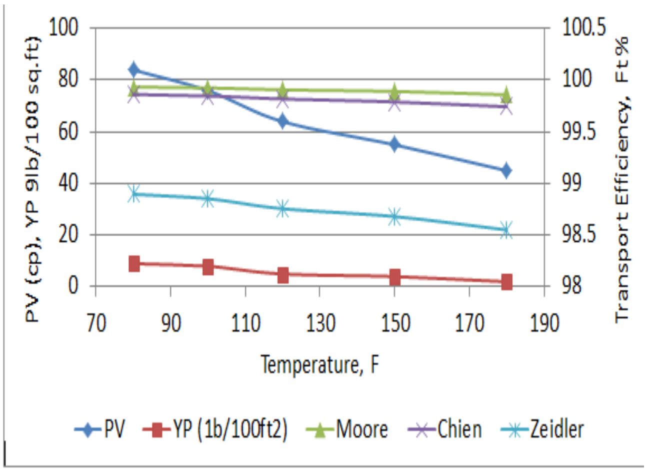


Fig 8: Variation of Plastic viscosity, Yield Point and Transport Efficiency with Temperature for system of Mud B and Cuttings B

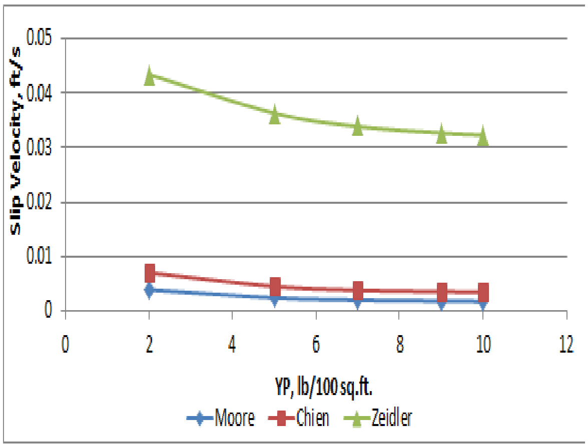


Fig 9: Variation of Slip Velocity with Yield point for system of Mud A and Cuttings A

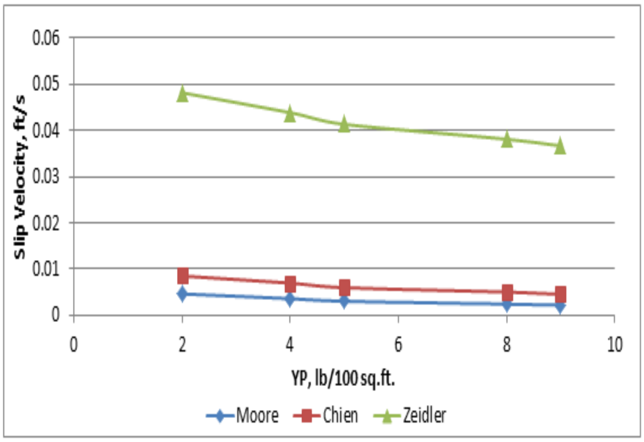


Fig 10: Variation of Slip Velocity with Yield point for system of Mud B and Cuttings A

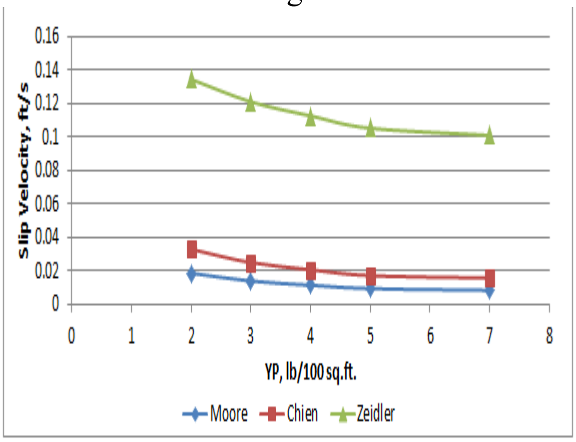


Fig 11: Variation of Slip Velocity and yield point for system of Mud A and Cuttings B

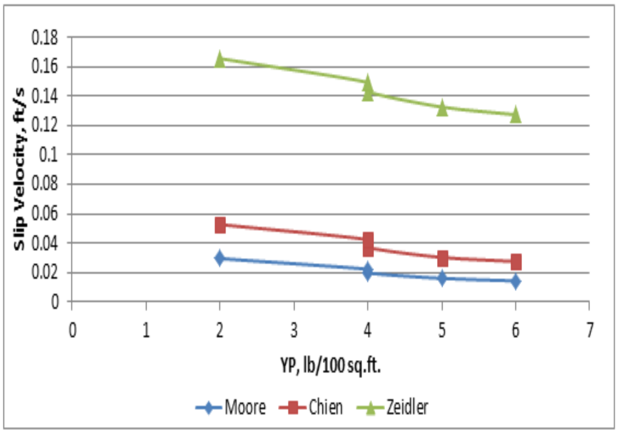


Fig 12: Variation of Slip Velocity and yield point for system of Mud A and Cuttings B

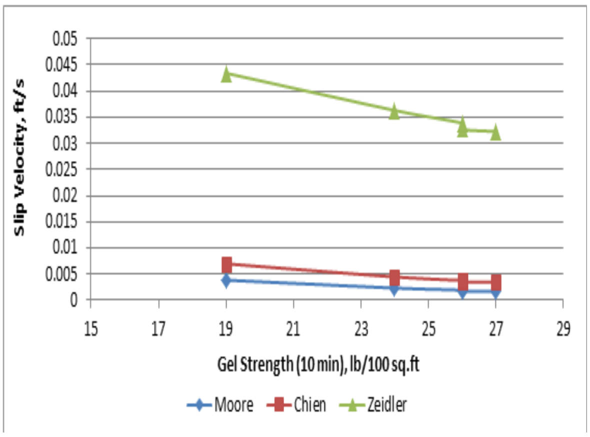


Fig 13: Variation of Gel strength and Slip Velocity for system of Mud A and Cuttings A

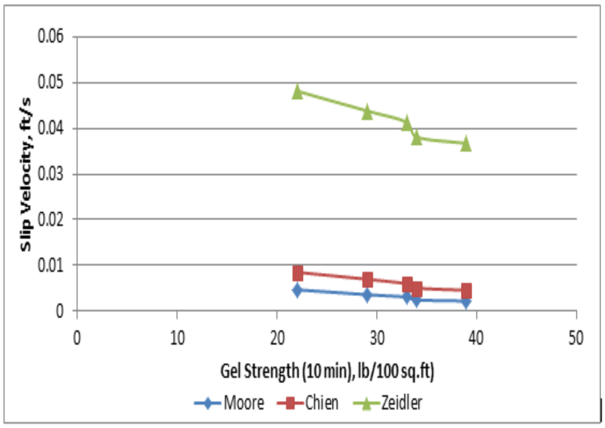


Fig 14: Variation of Gel strength and Slip Velocity for system of Mud B and Cuttings A

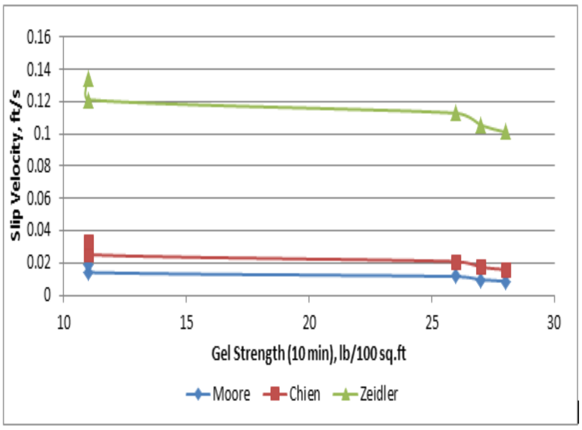


Fig 15: Variation of Gel strength and Slip Velocity for system of Mud A and Cuttings B

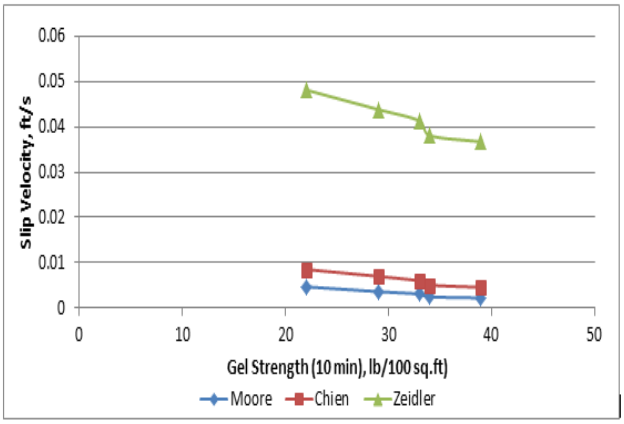


Fig 16: Variation of Gel strength and Slip Velocity for system of Mud B and Cuttings B

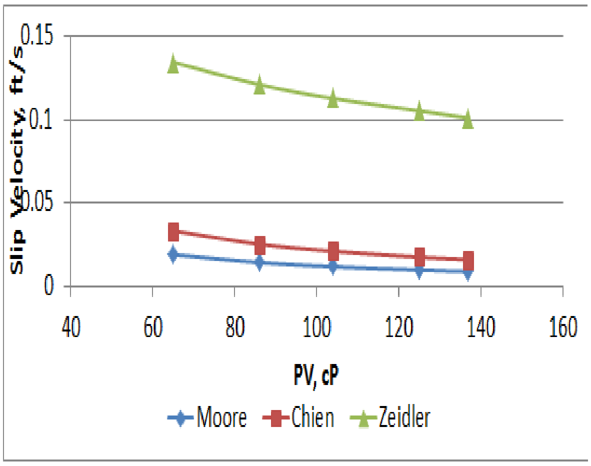


Fig 17: Variation of plastic viscosity and Slip Velocity for system of Mud A and Cuttings B

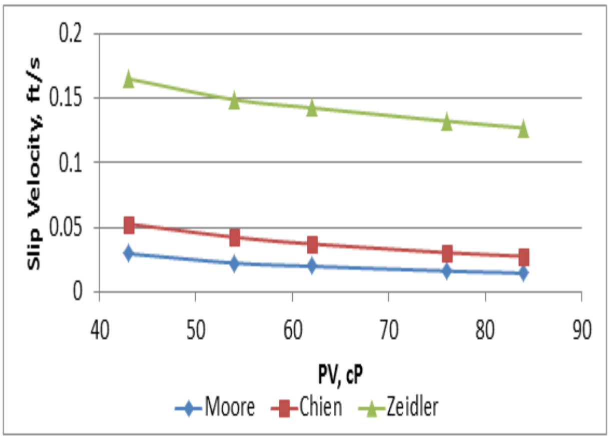


Fig 18: Variation of plastic viscosity and Slip Velocity for system of Mud B and Cuttings B

From Figure (1) above, it can be seen that the yield point and plastic viscosity decreases with increasing temperature and in laminar, fluid rheology contribute immensely to the efficiency in cuttings transportation. In Becker et al (1999), it was concluded that the mud rheology considerably affect cuttings transport positively in the laminar flow regime in vertical wellbore, while it has no significant effect on the cuttings transport when the flow regime was turbulent. Though there's more marked variation for the plastic viscosity than there is for the yield point. It is also observed that the slip velocity increases as these rheological properties decrease. However, there appears to be greater corresponding change in the results obtained from the Zeidler model than those obtained from the Chien and Moore models for each Plastic viscosity variation. As such, it can be postulated that the Slip velocity computed with the Zeidler model is characterized by a strong negative correlation with Plastic Viscosity. From Figures (1-4), there is less variation in the slip velocity calculated with the Chien and Moore models with plastic viscosity, with the Moore model results appearing most resistive to change. The yield point on the other hand, appears to be less variant. Similar but reversed trends are observed in the Figure (5-8) for transport efficiency. The variation trend for each of these rheological parameters with slip velocity are isolated and depicted in the ensuring plots.

Figure (13-16) shows that the slip velocity decreased with increasing gel strength. This implies that stronger gels impede cuttings slippage. However, for these mud systems, the impact of gel strength is a lot lower than would be desirable. Consequently, a mud engineer cannot rely solely on improving gel strength to stop cuttings slippage for the mud system being studied. The generality of this is not ascertained herein this study.

Similar observations and analyses can be reached for the other three fluid systems as shown in the figures. A striking feature of Figure (17-18) is the very similar changes in the slip velocity from Zeidler model with Plastic viscosity. Both plots appear to change by the exact same manner showing a very strong dependence of Zeidler slip velocity on the Plastic viscosity. This would imply that plastic viscosity measurements be carefully performed when the Zeidler model is proposed for Cuttings Slip and transport analysis.

3.2 Variation of Transport Parameters with Temperature

The results obtained from the computation of cuttings transport parameters [slip velocity, transport efficiency etc.] are presented in this section. The computations are done using the Moore, Chien and Zeidler models for slip velocity.

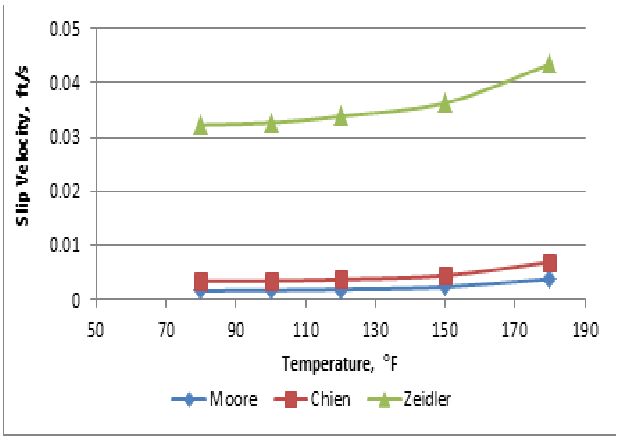


Fig 19: Variation of Slip Velocity with Temperature for system of Mud A and

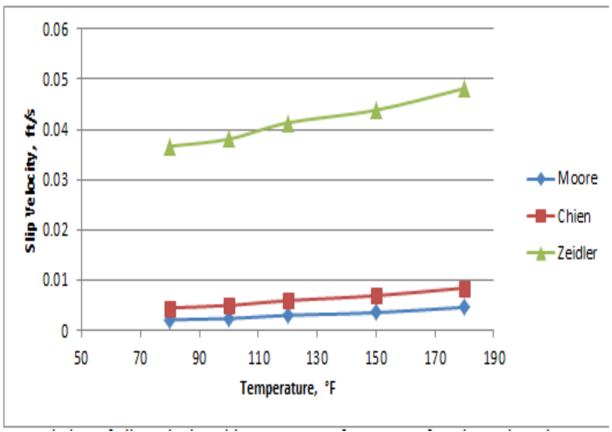


Fig 20: Variation of Slip Velocity with Temperature for system of Mud B and

Cuttings A

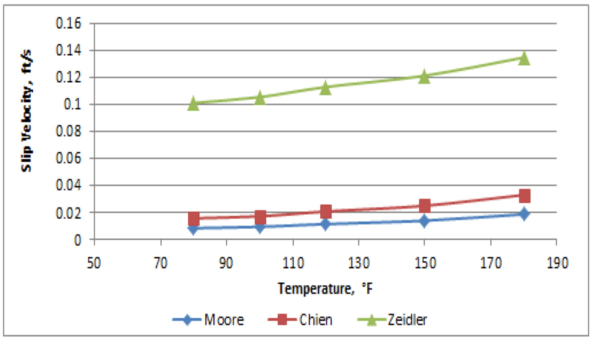


Fig 21: Variation of Slip Velocity with Temperature for system of Mud A and Cuttings B

Cuttings A

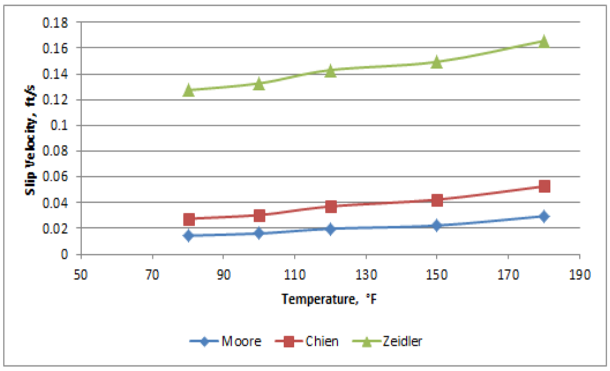


Fig 22: Variation of Slip Velocity with Temperature for system of Mud B and Cuttings B

The effect of temperature variation on the cuttings slip velocity for the fluid system composed of Mud A and Cuttings A is presented in Fig (19). The trend observed indicates an increase in slip velocity with temperature. This would imply that the slippage of cuttings through the mud increases with an increase in mud temperature. This can be attributed to the simultaneous reduction in mud viscosity associated and other rheological parameters with increasing temperature. Consequently, these less viscous fluid systems have less internal friction needed to carry cuttings to the surface, resulting in the increased slip velocity. It can also be seen that there is less discrepancy between the values obtained using the Moore and Chien models, both of which shows relatively larger differences when compared to Zeidler model results.

Similar observations are made for the fluid composed of Mud B and Cuttings A. this is illustrated in Fig (20). For the fluid systems containing Cuttings B, a higher slip velocity was observed. This reflects an increase in cuttings slippage through the mud. Furthermore, it is also a direct corollary of the lower density of the Cuttings B relative to that of Cuttings A [SG of B = 2.463, S.G. of A = 2.525]. This leads to a correspondingly lower density for the composite fluid system.

3.3 Validation of Model Results

The sensitivity was measured using two parameters: the contribution to variance and the rank correlation coefficient for the first fluid system comprised of Mud A and Cuttings as a case study. The summary results of the sensitivity run were based on the five cuttings transport parameters selected and are presented in the Table (5) below.

Table 5: Results of Sensitivity of Slip Velocity to Cuttings Properties and Fluid Rheology

Assumptions	Contribution To Variance (%)			Rank Correlation		
	Moore	Chien	Zeidler	Moore	Chien	Zeidler
Size of Cuttings (μm)	93.65	91.47	91.46	0.9562	0.9594	0.9562
Specific gravity (SG)	6.11	6.35	7.76	0.2785	0.2527	0.2785
Mud Weight (ppg)	0.09	1.79	0.64	-0.0802	-0.1344	-0.0802
Plastic Viscosity (cp)	0.08	0.35	0.08	-0.0275	-0.0593	-0.0275
Q (gpm)	0.07	0.03	0.06	0.0253	0.0187	0.02534

4. CONCLUSION

For this work, the effect of mud rheology and cuttings size on cutting transportation in vertical wells has been evaluated using cuttings samples gotten from a Niger-Delta field called Anieze North field and operated by Sterling Global limited. This work integrates experimental measurement with the use of existing formulations to test and study the behaviour of two different fluids rheology on the transportation of two different cuttings samples of 400um and 1000um at 10% concentration. The analysis of results generated can be summarized as follows:

1. Rheology of mud has a major role in the efficient transport of cuttings for a laminar flow pattern. To ensure an efficient hole cleaning, there is the need to maintain a high viscosity in laminar flow.
2. The downhole temperature reduces fluid rheology which in turn, reduces the carrying capacity of the fluid.
3. The result of the simulation and the sensitivity analysis showed that the greater the cuttings size, the more the slip velocity and the less the transport efficiency. It also showed that the efficiency of the cuttings transport is dependent on the design of the drilling fluid in relation to the cuttings sizes.

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APPENDIX

List of Nomenclatures

- F = Frictional Factor
- F_T = transport ratio
- F_{Te} = transport efficiency
- OBM = Oil Based Mud
- n = fluid behavior index
- K= Consistency index
- d1 = diameter of the string, in
- d2 = diameter of the annulus, in
- ROP = Rate of penetration, (ft/h), (m/h)
- V = Flow velocity, (ft/min), (m/s)
- $\overline{V_T}$ = transport velocity
- Va = Average velocity in annulus, (ft/min), (m/s)
- Vcrit = Critical viscosity, (ft/min,), (m/s)
- Vs = Vslip= Slip velocity of cuttings, (ft/min), (m/s)
- YP = Yield point, (lbf/100 ft2), (Pa)
- fluid layers, (ft/min), (m/s)
- μ = Fluid viscosity, (cP), (Pa*s)
- μa = Apparent Viscosity, (cP), (Pa*s)
- μ_p= plastic viscosity (pv),
- ρ = ρ_f = Fluid density, (lbm/gal), (kg/m3)
- ρc = ρ_s = Density of cuttings, (lbm/gal), (kg/m3), (g/cm3)