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Particle settling in power law fluids

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ABSTRACT

This research was aimed at investigating solid particles settling in drilling fluid - Power law fluid in relation to rheological properties of the fluid. Fluid of various densities and rheologies were prepared in the laboratory. Hydroxyl methyl cellulose (HEC) was used in this proportion 5.0, 2.5, 1.5, and 0.5 g/liter to change the rheology of the fluid with a fluid density range from 1.003 to 1.513 g/cm^3. The results show that larger particles diameter enhance the particle settling behaviour and increases settling velocities. Also increased fluid density reduces particle settling velocity and increases fluid viscosity. The largest effect on the particle settling is achieved at high fluid viscosity. Therefore, it is recommended that fluids for cutting removal should be designed with a higher consistency index K in order to increase the fluid viscosity and thereby overcome the settling behaviour.

Introduction

The knowledge of the terminal velocity of solids in liquid is required for many industrial applications and drilling operations. Typical examples include hydraulic transport systems for coal and ore transportation, drilling for oil and gas, mineral processing, geothermal drilling, solid-liquid mixing etc. Terminal velocity, drag and gravity forces and shear stresses are affected by particle properties and the rheology of the circulation fluids. (Darley and Gray, 1988).

The settling behavior changes due to irregular shape of the solids and depends on the density of the fluid. In drilling fluids, interaction between the fluid phases creates a complex dependency between shear stress and shear rate. Cuttings particles tend to settle downward responding to the gravity force while some other forces acting on the cuttings, work to overcome settling, like the drag, lift and buoyancy forces. (Clark and Bickham, 1994).

Moreover, when flow circulation is stopped, for drill pipe change or other purposes, the mud must be designed to maintain the cuttings suspension and limit sedimentation. The fluid exhibits a yield stress that can support the weight of the cuttings. Settling mechanisms in shear-thinning fluid with yield stress are not well understood. For example, many settling velocity corrections exist for one particle in non Newtonian fluids, but do not adequately match with measurements [Alfren *et al.*, 1995].
In drilling operations, cuttings transport, aggregation of settled particles due to low cutting fluidity and high static fraction results in stationary bed or motion (Ramadan, 2003). Accumulation of the settled particles in the conduit section reduces the flow area which becomes non – circular. Taking example of the oil well drilling application as a consequence, this will generate many problems such as low rate of penetration, (ROP) overload of pumps, excessive drill pipe and tools wear, lose of circulation due to transient hole blockage, extra mud additive costs, problems in cementing and difficulties in running casing operations, waste of the limited energy available to the drill bit and hole packing off. These problems may finally lead to early termination of drilling operation and eventual abandonment of the well.

The required minimum velocity to transport solids depends on the amount and behavior of settled particles (Belavadi and Chukwu, 1994). Indeed cutting particle settling velocity is an important variable in cutting transport. In drilling operations, the drilling fluids exert a force called ‘drag force’ on the moving sphere in the fluids. This study investigates the settling velocities in Power law fluids to enhance effective cuttings removal from the hole.

Drill Cutting Sizes

Belavadi and Chukwu (1994) conducted a study with three different cutting sizes and concluded that the removal of small size cutting particles is greatly enhanced by pipe rotation when drilling with high density mud circulated at high flow rates. They also found out that cuttings sizes had moderate influence on cutting transportation. They concluded that fine particles are the easiest to clean out while spherical particles with an average size of 7.6 mm pose the greatest difficulty for solids removal.

Rheology

Darley and Gray (1988) described the term Rheology as the properties of a given drilling fluid and define it as the science and study of the deformation and flow of matter. Rheology is important to consider experiencing the best drilling effect. This is the reason why mud rheology is constantly monitored while drilling and adjusted with additives to meet the needs of the operation.

There are basically three types of drilling fluid Water based mud (WBM), Oil based mud (OBM) and synthetic oil based mud (SOBM). Water based mud are preferred in all cases because it is more environmentally friendly, but there are still many occasions where oil based mud have the best suited properties. Water based mud have still not been able to provide the same levels of shale inhibition and lubrication offered by oil based mud. Because of long horizontal wells being drilled often from a fixed platform in the middle of the reservoir, oil based muds are the only mud that can be used for this kind of wells effectively, safe and economically. POBM is an answer to the

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restrictions on the discharge of cuttings drilled out from the hole by using OBM. It has a enhanced biodegradability and reduced bio accumulation and toxicity to be more environmentally friendly, but also has similar properties as the OBM such as good lubricating properties. For the drilling of the world record breaking C2 well at the Statfjord field they used an ester based drilling fluid, which is a SOBM (Bourgoyne et al , 1991). The synthetic oil based muds seems to be the perfect solution to the restrictions regarding oil based mud, but it has some drawbacks. In alkaline conditions and at high temperatures the chemical formula for SOBM can break down and lose the requested drilling fluid properties.

Rheology Models

According to (Ford and Peden, 1990), the three drilling fluid types mentioned above, WBM, OBM and SOBM, can be divided into different rheology models to describe the shear stress versus the shear rate behaviour. The most commonly used rheological models are: Newtonian, Bingham Plastic, Power Law and Herschel-Bulkley.

Rheological Differences

Figure 1 shows the differences between the most common flow models; Newtonian, Bingham Plastic and Power Law. This figure gives a description on how the variables; viscosity, plastic viscosity, shear stress and yield shear stress affect the different flow models. The flow model of a typical drilling fluid is also illustrated in the figure but the Herschel-Bulkley model is not represented. It would have had the shape of a Power Law model and the starting point at the yield stress from the Bingham model.

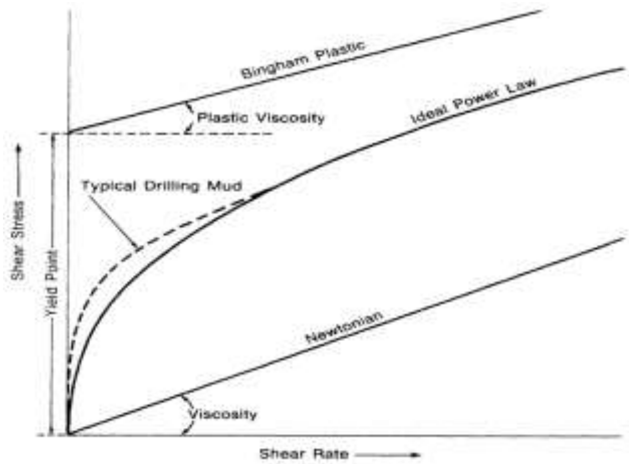

Figure 1: Ideal consistency curves for the most common flow models (Ramadan, 2003)

Drag coefficient of a falling sphere

When a sphere falls, it initially accelerates under the action of gravity (Doan *et al*, 2003) the resistance to motion is due to the shearing of the liquid passing around it. At some point, the resistance balances the force of gravity and the sphere falls at a constant velocity. This is the terminal velocity of the particle, defined as:

$$V_s = \frac{d^2 g(\rho_s - \rho_f)}{6\pi\mu} \qquad (1)$$

Where,

Vt = terminal velocity μ = viscosity, g = gravity

ρ_s =density of the sphere material

ρ_f =density of fluid

d = sphere diameter.

The concept of drag coefficient is normally used to define the viscous resistance as:

$$C_D = \frac{Resistance\ force}{Dynamic\ pressure\ x\ projected\ Area} \qquad (2)$$

Drag coefficient, *CD* , is found by using Figure 2. The Figure presents the relationship between drag coefficient and the Reynolds number for particles for Newtonian fluids. To find the correct drag coefficient the Reynolds number must be calculated

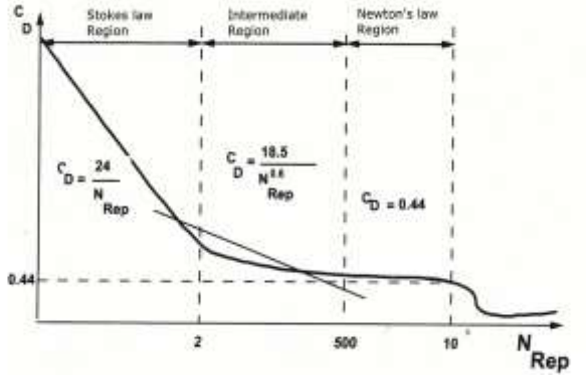

Figure 2: C_D versus N_{rep} for Particle setting in Newtonian Fluids

Materials and Methodology

Materials and Equipment: Glass cylinder (1m), Mud balance, Mixer, Stirring rod, measuring cup, Sieve, Fann Viscometer, Venire Caliper , Stopwatch, HEC (Hydroxyl Ethyl Cellulose), cutting particles.

Classification of cuttings or solids sizes

The parameter involved in the study of the settling velocity pertaining to the solid particles is the particle diameter. The cuttings sizes used in this study were obtained from North Cape minerals, product of Norway, processed in Trondheim, Norway. A hand-held sieving device was used to measure the size of the cuttings. Table 1 shows the different particle diameters

Table 1: Classification of cuttings sizes

Source	Particle size	Particle diameter, cm
Norway	Small	0.055
Norway	Medium	0.355
Norway	Large	0.613
Norway	Very large	0.692

Fluid Rheological Properties

Four different fluid rheologies were prepared and used in the experiment. Polymer HEC was added to water and thoroughly mixed with the aid of a high speed mixer to create Power Law fluids with four different viscosities. HEC was successfully used to create Power Law fluid in the study done by (Ford and Peden, 1990). The fluids used in the experiment are presented in Table 2.

Table 2: Calculated values for the rheological models

Fluid	Rheology Model	Fluid Behavior Index, n	Consistency Index, K
Fluid 1: HEC, 5g/liter	Power Law	0.63	0.5112
Fluid 2:HEC, 2.5g/liter	Power Law	0.57	0.2433
Fluid 3:HEC,1.5g/liter	Power Law	0.65	0.2066
Fluid 4:HEC, 0.5g/liter	Power Law	0.66	0.0306

Densities of the Fluid Phase

In order to investigate fluid density effect on particle settling, different quantities of barite were added to 350 mL of

Fluid as shown in Table 3. The density of the fluid was determined using mud balance.

Table 3: Densities of the fluid

Quantity of barite (g)	Fluid density g/cm3
15.5	1.003
22.5	1.105
35.5	1.186
48.5	1.513

The following test procedures were applied in running the experiments:

- Mesh sieve of various sizes along with Venire Caliper from drill cutting sizes.
- The glass tube was calibrated from 0 to 1m (100cm)
- The glass tube was then filled with fluid to 80 cm mark
- The glass tube was filled with fluid and mounted on a table
- Cutting particles were then dropped into the glass tube carefully and gently
- The Stopwatch was simultaneously started to record the actual particles settling time
- Particles were allowed to settled at the 80 cm mark in order to reach its terminal velocity
- For each particle size, the experiment was repeated five times in order to avoid error
- The terminal velocity was then calculated
- This same procedure was repeated for all the particles settling both in Newtonian and non-Newtonian fluids.

Figure 3. Experimental Set Up

Results And Discussions

Effect of Particle Size

Table 1 – 4 indicate the calculated results for four particle sizes settling at low fluid density. To examine the particle size effect, the settling behavior was encountered at fluid viscosity K = 0.2066 Pa.s^n, n = 0.57. Figure 4 shows the settling results for four particle sizes which flow at low fluid density of 1.003 g/cm^3. It is observed that high particle size has high settling velocity.

Table 4. 0.055 cm particle settling at low fluid density

	Power law index, n		0.57
	Consistency index, K (Pa.s^n)		0.2066
	Fluid density (g/cm^3)		1.003
	Particle size (cm)		0.055
Length (cm)	**Time (s)**	**Velocity (cm/s)**	**N_{Rep}**
80	800	0.1	0.026067
80	800	0.1	0.026067
80	800	0.1	0.026067
80	800	0.1	0.026067
80	800	01	0.026067

Table 5. 0.355 cm particle settling at low fluid density

	Power law index, n		0.57
	Consistency index, K (Pa.s^n)		0.2066
	Fluid density (g/cm^3)		1.003
	Particle size (cm)		0.355
Length (cm)	**Time (s)**	**Velocity (cm/s)**	**N_{Rep}**
80	10.0	8.0	39.73192
80	10.0	8.0	39.73192
80	10.0	8.0	39.73192
80	10.0	8.0	39.73192
80	10.0	8.0	39.73192

Table 6. 0.613 cm particle settling at low fluid density

	Power law index, n		0.57
	Consistency index, K (Pa.s^n)		0.2066
	Fluid density (g/cm^3)		1.003
	Particle size (cm)		0.613
Length (cm)	**Time (s)**	**Velocity (cm/s)**	**N_{Rep}**
80	4.8	16.50	152.7373
80	4.8	16.50	152.7373
80	4.8	16.50	152.7373
80	4.8	16.50	152.7373
80	4.8	16.50	152.7373

Table 7: 0.692 cm particle settling at low fluid density

	Power law index, n		0.57
	Consistency index, K (Pa.s^n)		0.2066
	Fluid density (g/cm^3)		1.003
	Particle size (cm)		0.692
Length (cm)	**Time (s)**	**Velocity (cm/s)**	**N_{Rep}**
80	4.2	19.00	200.2483
80	4.2	19.00	200.2483
80	4.2	19.00	200.2483
80	4.2	19.00	200.2483
80	4.2	19.00	200.2483

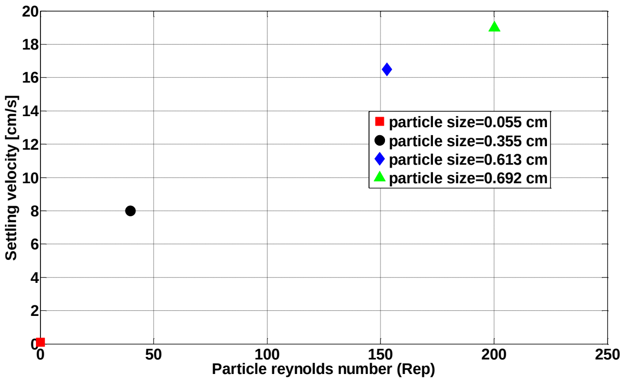

Figure 4. Particle size effect on settling at low fluid density (1.003 g/cm^3)

Table 8–11 indicate the calculated results for four particle sizes settling at high fluid density. At high fluid density of 1.513 g/cm^3, result of all particle size were in low settling behavior compared to their behavior at lower density of 1.003 g/cm^3, as shown in Figure 5.

Table 8. 0.055 cm particle settling at high fluid density

	Power law index, n		0.57
	Consistency index, K (Pa.s^n)		0.2066
	Fluid density (g/cm^3)		1.513
	Particle size (cm)		0.055
Length (cm)	**Time (s)**	**Velocity (cm/s)**	**N_{Rep}**
80	800	0.10	0.039322
80	800	0.10	0.039322
80	800	0.10	0.039322
80	800	0.10	0.039322
80	800	0.10	0.039322

Table 9. 0.355 cm particle settling at high fluid density

	Power law index, n		0.57
	Consistency index, K (Pa.s^n)		0.2066
	Fluid density (g/cm^3)		1.513
	Particle size (cm)		0.355
Length (cm)	**Time (s)**	**Velocity (cm/s)**	**N_{Rep}**
80	38.1	2.10	8.851818
80	38.1	2.10	8.851818
80	38.1	2.10	8.851818
80	38.1	2.10	8.851818
80	38.1	2.10	8.851818

Table 10. 0.613 cm particle settling at high fluid density

	Power law index, n		0.57
	Consistency index, K (Pa.s^n)		0.2066
	Fluid density (g/cm^3)		1.513
	Particle size (cm)		0.613
Length (cm)	**Time (s)**	**Velocity (cm/s)**	**N_{Rep}**
80	20.0	4.00	30.36875
80	20.0	4.00	30.36875
80	20.0	4.00	30.36875
80	20.0	4.00	30.36875
80	20.0	4.00	30.36875

Table 11: 0.692 cm particle settling at high fluid density

	Power law index, n		0.57
	Consistency index, K (Pa.s^n)		0.2066
	Fluid density (g/cm^3)		1.513
	Particle size (cm)		0.692
Length (cm)	**Time (s)**	**Velocity (cm/s)**	**N_{Rep}**
80	13.3	6.00	58.10928
80	13.3	6.00	58.10928
80	13.3	6.00	58.10928
80	13.3	6.00	58.10928
80	13.3	6.00	58.10928

Thus, such increase on the fluid density from 1.003 to 1.513 g/cm^3 was capable of suspending larger cuttings and reducing the settling behavior. The settling velocity of larger particle size particle 0.692 cm was reduced from 19.5 to 6.5 cm/s.

Moreover, flow of small size particles of 0.055 cm had low fluid density. Small size particles had lower settling velocity compared to the large-sized particles which has a significant settling velocity of 19.5 cm/s. Large-sized cuttings are found to settle more than small-sized cuttings (Martins et al, 1999) observed that removal of larger cuttings is the most difficult. On the other hand (Munson and Young, 2003) announced that contribution of the cutting size effect depend on the direction of the fluid flow, as fluid flow vertically preventing the easy settling of small size cuttings.

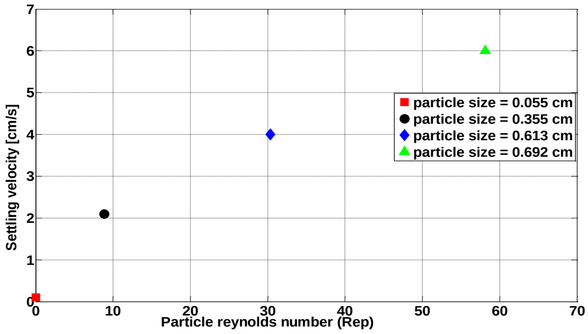

Figure 5. Particle size effect on settling at high fluid density (1.513 g/cm^3)

Effect of Fluid Density

Table 12 – 15 indicate the calculated results for 0.355 cm particle size settling at different fluid densities. To inspect the effect of fluid density, medium particle size of 0.355 cm diameter was used. Maintaining the power law fluid viscosity at K= 0.2066 Pa.s^n, n = 0.57, Figure 6 demonstrated that the particle settling velocities were high at low fluid density.

Table 12. Particle settling at fluid density of 1.003 g/cm^3

	Power law index, n		0.57
	Consistency index, K (Pa.s^n)		0.2066
	Fluid density (g/cm^3)		1.003
	Particle size (cm)		0.355
Length (cm)	**Time (s)**	**Velocity (cm/s)**	**N_{Rep}**
80	3.1	25.50	58.10928
80	3.1	25.50	58.10928
80	3.1	25.50	58.10928
80	3.1	25.50	58.10928
80	3.1	25.50	58.10928

Table 13. Particle settling at fluid density of 1.105 g/cm^3

	Power law index, n		0.57
	Consistency index, K (Pa.s^n)		0.2066
	Fluid density (g/cm^3)		1.105
	Particle size (cm)		0.355
Length (cm)	**Time (s)**	**Velocity (cm/s)**	**N_{Rep}**
80	3.6	22.50	192.0451
80	3.6	22.50	192.0451
80	3.6	22.50	192.0451
80	3.6	22.50	192.0451
80	3.6	22.50	192.0451

Table 14. Particle settling at fluid density = 1.186 g/cm^3

	Power law index, n		0.57
	Consistency index, K (Pa.s^n)		0.2066
	Fluid density (g/cm^3)		1.186
	Particle size (cm)		0.355
Length (cm)	**Time (s)**	**Velocity (cm/s)**	**N_{Rep}**
80	4.7	17.00	138.0532
80	4.7	17.00	138.0532
80	4.7	17.00	138.0532
80	4.7	17.00	138.0532
80	4.7	17.00	138.0532

Table 15. Particle settling at fluid density = 1.513 g/cm^3

	Power law index, n		0.57
	Consistency index, K (Pa.s^n)		0.2066
	Fluid density (g/cm^3)		1.513
	Particle size (cm)		0.355
Length (cm)	**Time (s)**	**Velocity (cm/s)**	**N_{Rep}**
80	6.6	12.20	109.5856
80	6.6	12.20	109.5856
80	6.6	12.20	109.5856
80	6.6	12.20	109.5856
80	6.6	12.20	109.5856

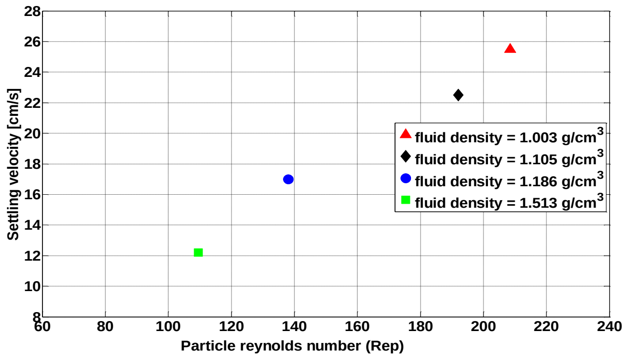

Figure 6. Fluid density effects on particle settling (particle size = 0.355 cm)

The lowest settling velocity was encountered at higher fluid density of 1.513 g/cm^3, where particle was found to settle at 9.5 cm/s. While at low fluid density of 1.003 g/cm^3, similar particle exerted 14.5 cm/s settling velocity. This agrees with (Cho et al, 2002) where increasing of the fluid density resulted in better hole cleaning, that indicate high fluid density is able to prevent high settling behavior. In addition, (Clark and Bickham, 1994) reported that increase of the fluid density allows for improvement of the buoyancy effect as low force would be required to exert on the settled cuttings.

Effect of fluid rheology

Table 16 – 19 show calculated results for 0.692 cm particle size settling at different fluid rheologies. Figure 7, shows the effect of rheological property. Generally the settling behavior increased with decreasing of the fluid viscosity. Larger particles of 0.692 cm fall faster in the lower fluid viscosity K = 0.0306 Pa.s^n, n = 0.66, as shown in Figure 7.

Table 16. Particle settling at fluid consistency index = 0. 0306 Pa.s^n

	Power law index, n		0.66
	Consistency index, K (Pa.s^n)		0.0306
	Fluid density (g/cm^3)		1.003
	Particle size (cm)		0.692
Length (cm)	**Time (s)**	**Velocity (cm/s)**	**N_{Rep}**
80	3.9	20.50	804.7344
80	3.9	20.50	804.7344
80	3.9	20.50	804.7344
80	3.9	20.50	804.7344
80	3.9	20.50	804.7344

Table 17. Particle settling at fluid consistency index = 0.2066 Pa.s^n

	Power law index, n		0.65
	Consistency index, K (Pa.s^n)		0.2066
	Fluid density (g/cm^3)		1.003
	Particle size (cm)		0.692
Length (cm)	**Time (s)**	**Velocity (cm/s)**	**N_{Rep}**
80	5.3	15.00	71.18146
80	5.3	15.00	71.18146
80	5.3	15.00	71.18146
80	5.3	15.00	71.18146
80	5.3	15.00	71.18146

Table 18. Particle settling at fluid consistency index = 0. 2433 Pa.s^n

	Power law index, n		0.57
	Consistency index, K (Pa.s^n)		0.2433
	Fluid density (g/cm^3)		1.003
	Particle size (cm)		0.692
Length (cm)	**Time (s)**	**Velocity (cm/s)**	**N_{Rep}**
80	10.7	7.50	53.00158
80	10.7	7.50	53.00158
80	10.7	7.50	53.00158
80	10.7	7.50	53.00158
80	10.7	7.50	53.00158

Table 19: Particle settling at fluid consistency index = 0.5112 Pa.s^n

	Power law index, n		0.63
	Consistency index, K (Pa.s^n)		0.5112
	Fluid density (g/cm^3)		1.003
	Particle size (cm)		0.692
Length (cm)	**Time (s)**	**Velocity (cm/s)**	**N_{Rep}**
80	20.0	4.00	6.329087
80	20.0	4.00	6.329087
80	20.0	4.00	6.329087
80	20.0	4.00	6.329087
80	20.0	4.00	6.329087

Increase in consistency index, K value from 0.2066 to 0.5112 Pa.s^n reduces the settling velocity for the particle size, 0.692 cm diameter from 17.5 to 4.5 cm/s. Such increase on K improved the viscosity and served to avoid settling of particle. Generally, slight increase of the fluid viscosity helped to suspend the particle. Increase on the fluid viscosity improves the fluid carrying capacity. Also they reported that reduction of the index behavior **n** increases the flow velocity and also thereby decreases cutting bed height i.e., resist settling behavior.

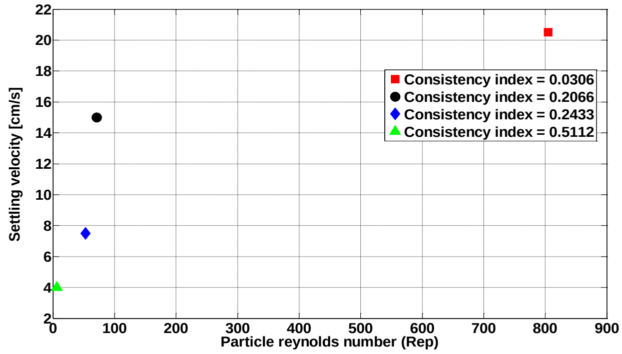

Figure 7. Effect of fluid rheology on settling behavior of particle (particle size = 0.692 cm)

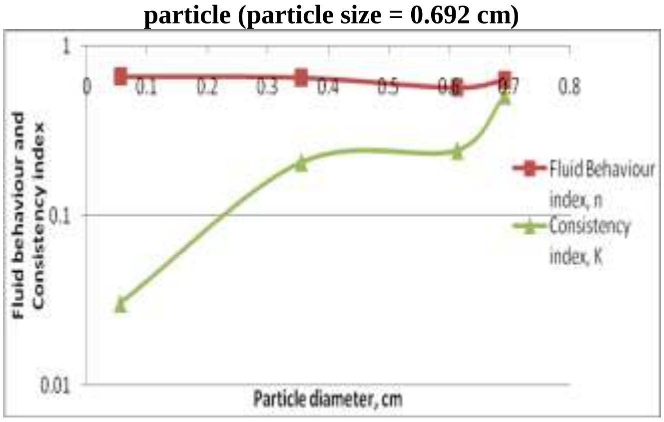

Fig. 8. Fluid behaviour and Consistency index K vs. particle diameter

When the fluid consistency index was lower, the fluid viscosity was also lower and the particle settling increases. But when the fluid consistency index becomes higher, the fluid viscosity increases, resulting in the particle settling becoming weaker and weaker as seen in figure 8.

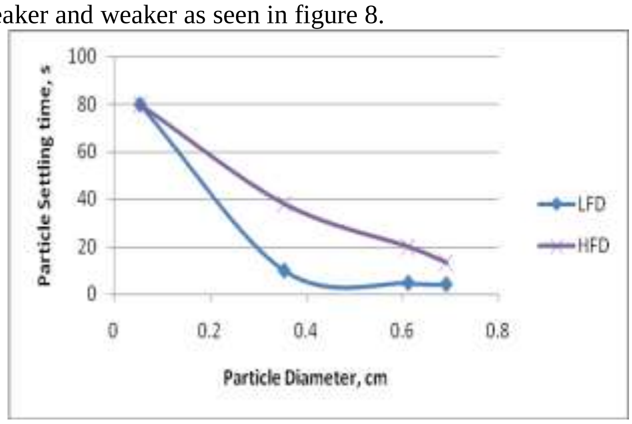

Fig. 9. Particle settling time vs. particle diameter for Low fluid and High Fluid Density

To verify the variations of the settling time of particles: small, medium and larger particles were also used. The experiments showed that smaller particles take longer time to settle than larger ones in both high and low fluid densities as indicated in figure 9. And the longer these particles are in the fluid, the more the particles are affected by the forces affecting the drilled cuttings transport (drag force, viscous force, buoyancy force etc). Larger particle move faster to settle than the smaller ones because they are less affected by the forces hindering the settling rate and cuttings removal from the hole.

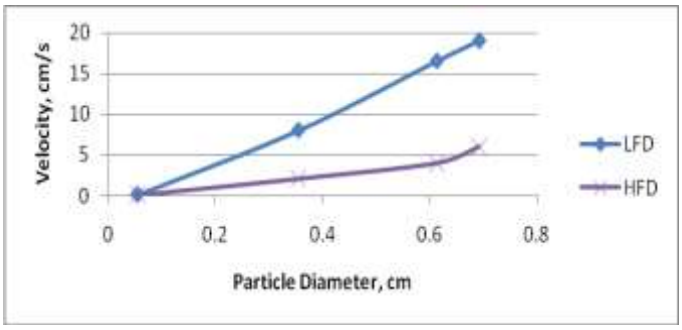

Fig. 10. Particle velocity vs. particle diameter for Low fluid and High Fluid Density

It is indicated that lower particles will increased the settling velocity than larger ones. But particles of the same sizes will slow down the settling velocity in high density fluid than low density fluid. The hydrodynamic interaction between the particles and the walls of the cylinder becomes more significant when there is an increased in the fluid density. This result brings a significant reduction in the settling velocity as indicated in figure 10.

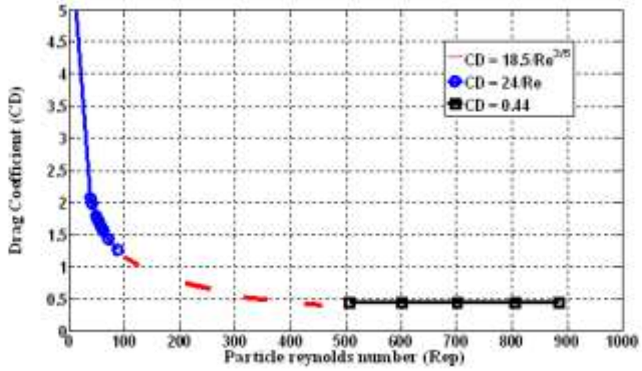

Figure 11: Relationship between Drag coefficient (CD) and Particle Reynolds number (Rep). Blue colour: particle size = 0.055 cm, fluid density = 1.513 g/cm^3; Red and Black colour: particle size = 0.692 cm, fluid density = 1.003 g/cm^3)

The relationship between drag coefficients and the Reynolds numbers for particle size of 0.055 cm and fluid density of 1.513 g/cm^3 (blue curve) is presented in Figure 10. Red and Black curves indicate the same relationship with particle size of 0.692 cm and fluid density of 1.003 g/cm^3.

For the blue section of the graph, Stokes flow applies in the settling of 0.055 cm particles, while Allen flow and a constant value of drag coefficient (CD = 0.44) applies in the settling of 0.692 cm particle sizes. It is interesting to note that Figure 11 shows some kind of resemblance of the relationship presented by (Doan et al, 2003) for particles Reynolds number and drag coefficient.

Conclusions

The settling velocity of solid in Power Law fluid as examined. Various fluid and solid particles were considered and their contributions in the settling phenomena were analyzed. The following conclusions were made:

Higher particle diameter sizes enhance the particle settling behavior. Large particle sizes resulted in higher settling velocities.

Increased in fluid density result in noticeable reduction in particle settling velocity especially in high fluid viscosity and small particle sizes. Large particle sizes resulted in higher settling velocities. The settling velocity for a given particle decreases as the fluid becomes more viscous, therefore, the settling rate curve for the viscous fluid shifts downward as the fluid viscosity increases. The settling velocity for a given particle decreases as the fluid becomes more viscous, therefore, the settling rate curve for the viscous fluid shifts downward as the fluid viscosity increases.

The largest effect on the particle settling is achieved at high fluids viscosity. As the fluid viscosity increases, particle settling becomes weak.

Recommendation

It is recommended that fluids for cuttings transportation should be designed with a higher consistency index K in order to increase the fluid viscosity and thereby overcome the settling behavior. Also in case of horizontal transport, lower viscosity is recommended to balance between turbulence and suspending capacity of the carrier fluid. As a future work, it will be interesting to develop a mathematical model of solids settling in a power law fluid and compare with the experimental results in this work.

Nomenclature

cm = centimetre
C_D = Drag coefficient
cm/s = centimetre per second
d = particle diameter
g = Acceleration due to gravity
g/cm^3 = gram per cubic centimeter
HEC = Hydroxyl ethyl cellulose
HFD = High Fluid Density
LFD = Low Fluid Density
K = Consistency index
m = meter
N_{Rep} = Reynolds Number of particles
n = Fluid flow behaviour
OBM = Oil Based mud
ρ_f = fluid density
ρ_s = Solid density
ROP = Rate of Penetration
V_t = terminal velocity
μ = liquid viscosity

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References

[1] Alfren, T., Heggen, S and Blikra, H. 1995. Pushing the Limits for Extended Reach Drilling: New World Record From Platform Statfjord C, Well C2. SPE Drilling & Completion, 10 (2):71–76. SPE–26350–PA.

[2] Belavadi, M.N. and G.A. Chukwu, 1994. Experimental study of the parameters affecting Drilled Cuttings Transportation in a vertical wellbore annulus. SPE Paper 27880. DOI: 10.2118727880-MS

[3] Bourgoyne , A. T. Jnr., Milheim, K. K., Chenevert, M. E. and Young, F. S. Jnr. Applied Drilling Engineering, SPE Textbook Series, and Volume 2. Richardson: Society of Petroleum Engineers.

[4] Cho, H., Shah, S.N. and Osisanya, S. O. 2002: “A three-segment hydraulic model for cuttings transport in Coiled tubing horizontal and deviated drilling”. J. Can. Petroleum Technol., 41: 32-39. DOI: 10.2118/02-06-03.

[5] Clark, R. and Bickham, K. 1994. A Mechanistic Mode for Cuttings Transport. Paper SPE 28306 presented at the SPE Annual Technical Conference and Exhibition, New Orleans, 25-28 September.

[6] Darley, H. and Gray, G. 1988. Composition and Properties of Drilling and Completion Fluids, fifth edition, .Huston: Gulf Professional Publishers.
[7] Doan, Q., Oguztoreli, M., Masuda, Y., Yonezawa,T.,Kobayashi, A., Naganawa, S. and Kamp, A. 2003. Modeling of Transient Cuttings Transport in Underbalanced Drilling (UBD). SPE Journal, 8 (2):160–170. SPE–85061–PA.
[8] Duan, M., Miska, S., Yu, M., Takach, N., Ahmed, R. and Zettner, C. 2006. Transport of Small Cuttings in Extended-Reach Drilling. Paper SPE 104192 presented at the 2006 International Oil & Gas Conference and Exhibition, New Orleans, 5-8 October.
[9] Ford, J and Peden, J. 1990. Experimental Investigation of Drill Cuttings Transport in Inclined Boreholes. Paper SPE 20421 presented at the SPE Annual Technical Conference and Exhibition New Orleans, 23-26 September.
[10] Martins, A., Santana, M. and Gaspari, E. 1999. Evaluating the Transport of Solids Generated by Shale Instabilities in ERW Drilling. SPE Drilling & Completion, 14 (4):254–259. SPE–59729–PA.
[11] Mims, M., Krepp, T., Williams, H. and Conwell, R. 2003. Drilling Design and Implementation for Extended Reach and Complex Wel ls. K&M Technology Group, LLC.
[12] Munson, B. R., Young, D. F. 2002. Fundamentals of Fluid Mechanic. John Wiley & Sons, Inc.
[13] Ramadan, A. 2003. Mathematical Modeling and Experimental Investigation of Solids and Cuttings Transport. PhD thesis, Norwegian University of Science and Technology, Trondheim, Norway.