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Investigation on The Particle Settling Velocity in Non-Newtonian Fluids

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Abstract: The present study targets to investigate the solid particles settling in relation to the particle shape and fluid rheological properties. The power law model of non Newtonian fluid represents the fluid phase according to the drill mud definition. The particles and the fluid properties and specifications are selected from previous works. The results characterized the scenario of solid in liquid settling behavior obtained from Chein's correlation of settling velocity for irregular shape. The result gives interpretation technique to design the drilling fluid with coordination to the cuttings sphericity concept to avoid bed formation problems. The final results sustain that settling increasing with the increasing on the shape factor. Small increase in fluid density can reduce particle settling velocity. Smaller particle size gives less settling velocity. Increasing of fluid viscosity will reduce a little bit in particle settling.

Key words: Sphericity, settling velocity, non newtonian fluids, power-law model, two- phase flow

INTRODUCTION

The two phase flow system can be classified under the complex flow category. As it is well known, the motion of particles in a viscous liquid represents one of the main focuses of engineering research. The behavior of settling particles is important in a variety of applications, from environmental to medical. However in such applications particle settling in a non-Newtonian power law fluid is issue of interest to many industrial applications, including chemical, food, pharmaceutical and petroleum industry. Settling involves in such practical applications occurs in engineering fields as petroleum, mining or even process engineering. In wells drilling operation slurry flow of dill-mud with the drilled cuttings in transport process is important application.

In transport applications the settling behavior represents an important problem especially when drill directionally. The solids transport for different particle sizes strongly influenced by wellbore deviation angle, as in Fig. 1.

Also terminal velocity, drag and gravity forces and shear stresses are affected by particle properties and the rheology of the circulation fluid. The settling behavior changes due to the irregular shape of the solids and depends upon the density and shape. In the drilling fluid, the interactions between fluid and solid phase create a complex dependency between shear stress and shear rate. Cutting particles tends to settle downward responding to the gravity force while some other forces acting on the cuttings and working to overcome settling those are Drag, Lift and Buoyancy.

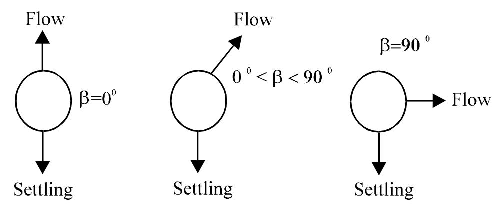

Fig. 1: Particle settling in vertical, inclined and horizontal flow

Moreover when flow circulation is stopped, for drill pipe change or other purpose, the mud must be designed to maintain the cuttings suspending 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 yet well understood. For example, many settling velocity correlations exist for one particle in non-Newtonian fluids, but do not match very well with measurements, (Peysson, 2004).

Accordingly, such analysis to investigate settling behavior of solids is also important while it encounters economic factors, as well, poor solid proceeding plant performance and erosion caused by particle impacts could add high cost in applications execution. Thus, the economics of wells drilling is related to the cleaning and this is also crucial to the industry.

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In the directional cuttings transport, aggregation of settled particles due to the low cutting fluidity and high static fraction results in stationary bed or motion (Ramadan *et al*., 2003). Accumulation of the settled particles in the conduit section reduces the flow area and high beds distorted the flow area which becomes non circular. Taking, e.g. the oil well drilling application, as a consequence, this will generate many problems. such as low ROP (rate of penetration), over load on mud pumps, excessive drill pipe and tools wear, loose 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, those problems may finally lead to terminate the drilling operation and loose the well itself. To prevent bed growing, increasing of the flow annular velocity or increasing the fluid viscosity assists the hole cleaning. While high flow rate is required to generate high shear force in order to erode beds. Relying only on bed erosion and predict the flow rate is necessary for efficient suspending of drilled cuttings and consequently the cuttings removal will be achieved. But some time high flow rate can occurs erosion and also could not be accomplished because of the pressure limitation (Li and Wilde, 2005). Excessive of annular velocity leads to erosion and high pressure drop. While operating at high pressure drop increases the hydrostatic pressure which may result in fracturing of the formation.

The required minimum velocity to transport solids depends upon the amount and behavior of settled particles. Indeed that cutting particle settling velocity is an important variable in cuttings transport. with noting that directional drilling applications required high annular velocities over vertical to enhance hole cleaning as saltation of the drilled solids would lead to such problems. The current study targets to investigate the settling behavior of non spherical particles under diverse conditions. Thus, Chien's settling velocity correlation (Chien, 1994) is employed to determine the settling of irregular shaped particles in various types of non Newtonian fluids.

THE SETTLING VELOCITY OF PARTICLE

In slurry flow the transport of solids depends upon such factors, as well the drilled cuttings transport affected by particles settling velocity in the carrier fluid. Settling velocity is important variable to predict transport especially in directional drilling as in Fig. 1. Some researchers worked in this area to obtain a correlation for settling velocity. (Shah, 1982) and (Shah, 1986) proposed a general correlations of settling velocity and drag coefficient as function of the index behavior of the non-Newtonian fluids. After that, (Peden and Luo, 1987) developed a generalized drag coefficient determination procedure for the power law fluids in laminar and transient region. That determination enables to predict the settling velocity of various shaped particles in the Newtonian and power law fluids.

Fig. 2: Irregular particle shape

Fang (1992) proposed a model for settling velocity in intermediate flow for Reynolds particle less than 100 according to a set of assumption in drilling applications.

In the drilling application, consideration should be given to both solid and fluid properties. A new correlation which describes the drilled cuttings settling velocity has been developed by Chien (1994), as:

$$v_p^2 + 4.458e^{(5.03\phi)}\left(\frac{\mu_e}{d_p\rho_f}\right)v_p - 19.45e^{(5.03\phi)}d_p\left(\frac{\rho_p}{\rho_f}-1\right)=0 \tag{1}$$

where, v_p is settling velocity of a particle, μ_e is effective viscosity of the fluid, d_p is the mean diameter of particle, ρ_f is density of the fluid, ρ_p is the particle density.

Chien' s correlation relates the drag and Reynolds number of particle. The correlation is valid to apply for both Newtonian and non Newtonian fluids. Non Newtonian properties into Chien's equation could be any of the different rheological models according to the effective viscosity of the fluid. The uniqueness of the new model is that it's involves the shape factor effect on particle terminal velocity for wide range of particle Reynolds number (0.001-10,000) (Chien, 1994).

The followings are essential to be described in study of the solid particle settling.

The Particle shape Factor (sphericity): Man-made and natural solid particle occur in almost non regular shapes, as shown in Fig. 2 (Anonymous). The characteristic size, shape and density of the particles greatly influence their dynamic behavior in flowing media. Various empirical factors employed in order to describe the resulted shape.

This provided some empirical description which is established by identifying the characteristics parameters from:

- volume
- surface area
- projected area
- projected perimeter

The available shape factors involved in criticisms as result of those different shapes may have the same shape factors. Therefore selection of the shape factors must be handled with more accuracy in relevance. Cited in (Yang, 2003a) the new ratio defined the degree of Sphericity by Wadell, 1933 is:

$$\phi = \frac{\text{Surface area of a shpere of equivalent volume as particle}}{\text{Surface aera of particle}} \quad (2)$$

The sphericity factor, ϕ, will provide brief clarification about the degree of deviation of the irregular particle from the true sphere shape (Cho, 2001). Hence, the factor for the regular sphere will reach the maximum one; while for non regular spherical particles will be less than one.

The drag coefficient for spherical solids particles moving in fluids is less than that for particles which is irregular in shape (non-spherical shape) and this implies that settling behavior is occurring faster for sphere (Cho, 2001).

Generally, crashed sand stone sphericity varies between 0.8-0.9 (Yang, 2003b). Drilled cuttings sphericity ranges between 0.75¯0.85 (Cho, 2001), so that the full range in the recent study will vary the shape factor between 0.75-0.9.

The particle reynolds number: Particles drag coefficient and particle Reynolds number are important when we deal with the saltaion behavior. Particle Reynolds number in non-Newtonian fluid (Cho, 2001) is defined as follows:

$$Re_p = \frac{0.1617 \rho v_p^{2-n} d_p^n}{36^{n-1} K} \quad (3)$$

where, K is consistency index of the fluid, n is fluid index behavior, Re_p is Reynolds number of the particle.

Fluid rheological properties: One of the common applications of the solid in liquid flow is the cuttings in drilling mud transportation. The drilling mud exhibits Thixotropy behavior where it displays a decrease in viscosity over time at a constant shear rate (Anonymous). Most of the drilling fluids are non Newtonian fluids, with viscosity decreasing as shear rate increase (Viloria Ochoa, 2006). This is similar behavior to the Pseudoplastic or shear thinning fluids. The non Newtonian fluids behavior is characterized by the power law models, as in (4). The behavior index, n is less than 1. In the power law model, the effective viscosity is given by as (Chien, 1994):

$$\mu_e = K\left(\frac{v_p}{d_p}\right)^{n-1} \quad (4)$$

where, μ_e is effective viscosity of the fluid. Therefore, the above viscosity model expression will be substituted for effective viscosity into Chien's correlation.

PROPERTIES OF THE SOLID AND LIQUID PHASES

Solid particles: The parameters involved in the study of the settling velocity pertaining to the solid particles are the particles diameter and density. The solid phase adapted data are gathered from (Li and Wilde, 2005), (Duan *et al*., 2006) and (Tomren *et al*., 1986), as shown in Table 1 and 2.

Table 1: Density of the solid phase

Source	Particle type		Particle diametercm	Particle density cm^{-3}
	Carbolite		0.076	2.71
SPE	Bauxite		0.076	3.56
94187	Light prppant 1	weight	0.076	1.25
	Light prppant 2	weight	0.076	1.75

Table 2: Classification of the cuttings sizes (diameter)

Source	Particle size	Particle diameter cm
SPE 104192	medium	0.4445
SPE 12123	small	0.012
SPE 12123	large	0.635
SPE 94187	small	0.076
	large	0.7

Table 3: Densities of the fluid phase

Source	Fluid density g cm^{-3}
	0.9982
	1.1983
M. W. Ali	1.4379
	1.7974
SPE 65488	1.1024

Table 4: Fluid phase rheological properties

Source	Power-law viscosity (Type)	K $Pa.s^n$	n
SPE 65488	low viscosity	0.2873	0.68
	low viscosity	0.0402	0.68
SPE 12123			
	Intermediate viscosity	0.2088	0.61
	high viscosity	0.4453	0.61

Fluid properties: Various types of fluid properties were selected from previous studies. The density and the rheological properties of the fluid phase were the main properties imbedded in the mathematical formulation of the present study. Different fluid properties were identified from previous studies in the well's drilling field (Ali, 2002) and (Cho, 2001) as illustrated in Table 3 and 4.

RESULTS AND DISSECTION

Chien's settling velocity relation for irregular shape particle is non linear equation. Consequently, special techniques of non linear equation solution and iteration procedures were employed in order to solve the correlation and related set of equations to obtain the settling results.

The iterative solution was conducted using Newton-Raphson method. This method extremely depends on the first guess point; and in the present application. Thus, the method could not give the physical right solution unless starting from the right guess as this method has some limitations (Yang *et al*., 2005). The outlines of the matlab algorithm shown in Fig. 3 were started with initial guess of the settling velocity.

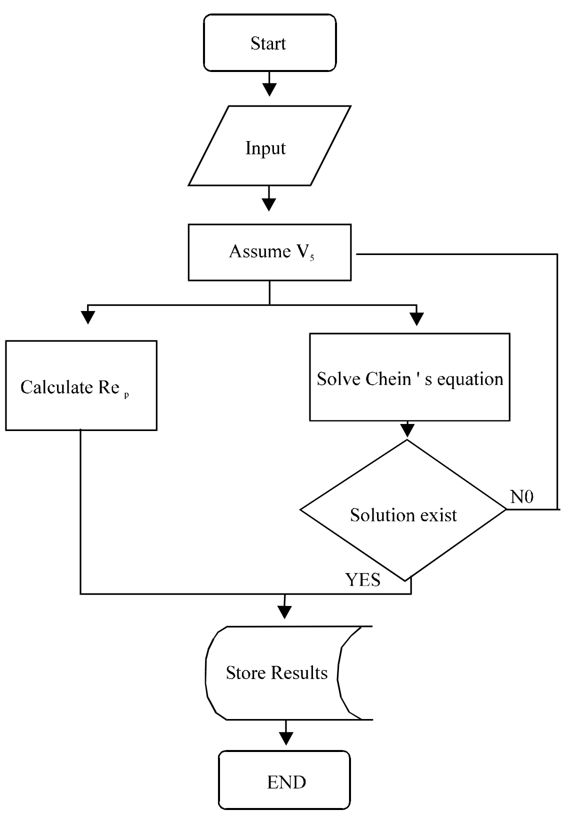

Fig. 3: The MATLAB program algorithm

Since the viscous and inertia forces are the most effective forces during the settling, the results are presented to show the variation of various parameters at different operating Re_p.

Effect of particle density: To vary the particle density intermediate fluid viscosity properties of K = 0.2088 Pa.s^n, n = 0.61 was engaged. Settling behavior for the different particle densities was examined using large and small particle sizes. Results of large particle size d_p= 0.7 cm were shown in Fig. 4. Study of four level of particle density reflected that large particle density merged with large cuttings size fall at high velocities. In addition, the shape factor effect was clearly appeared at the highest particles density. Where at low particle density 1.25g cm^{-3}, the contribution of the shape factor on settling velocity was

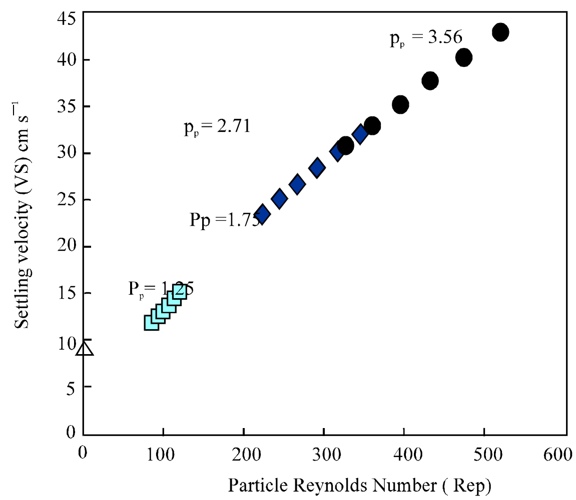

Fig. 4: Particle density effect on settling velocity of large particle sizes

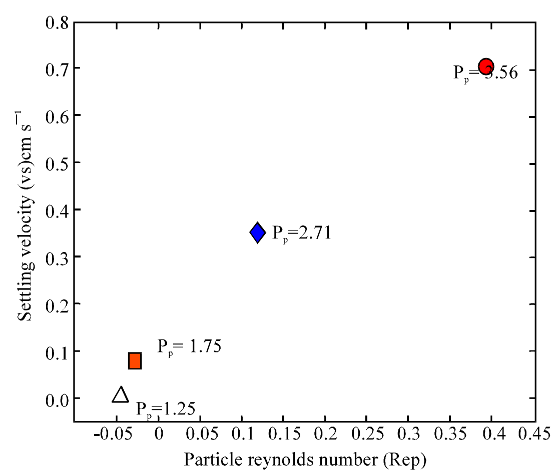

Fig. 5: Particle density effect on settling velocity of small particle sizes

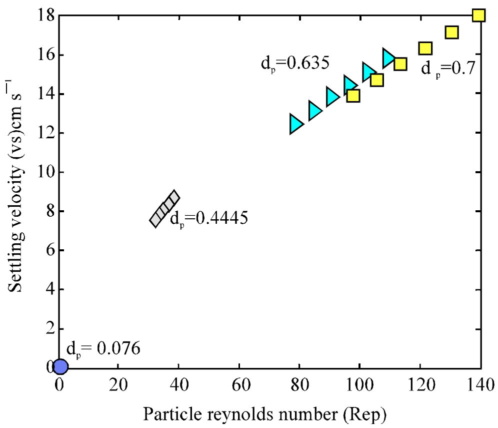

Fig. 6: Particle size effect on settling at low fluid density at various sphericity

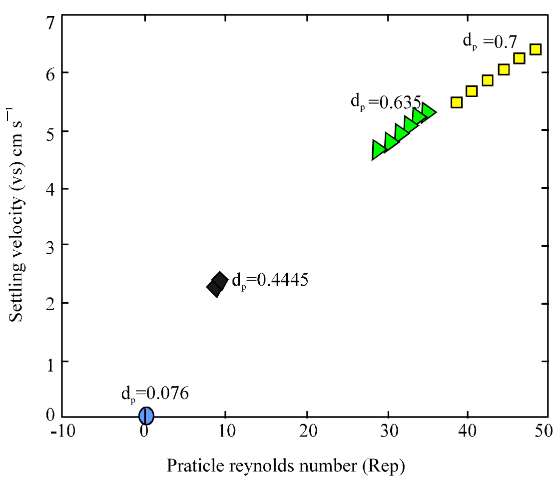

Fig. 7: Particle size effect on settling at high fluid density

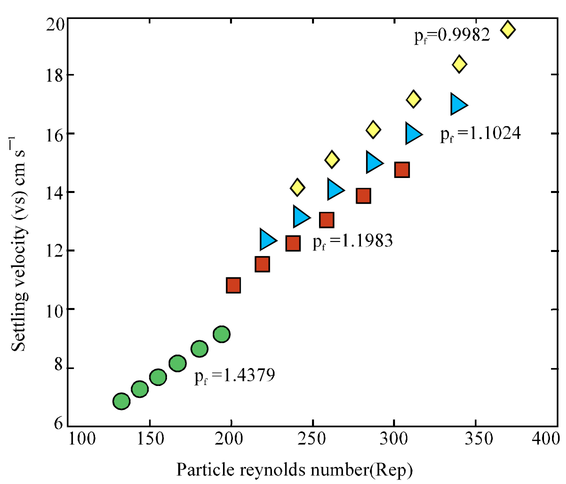

Fig. 8: Fluid density effects on particle settling with low fluid viscosity

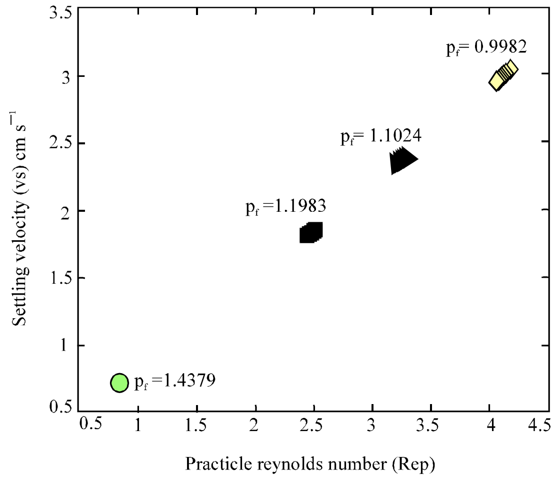

Fig. 9: Fluid density effects on particle settling with high fluid viscosity

small. Thus, settling velocity of low particle density 1.25g cm^{-3} of shape factor range 0.75-0.9 was changed in a range of 2.22 and 2.34 cm sec^{-1}. The settling velocity of the high particle density for the same sphericity range is observed to range between 30.82-42.95 cm sec^{-1}.

As shown in Fig. 5 flow of small particle size of 0.076 cm diameter with different particle density was lower. Highest particle density of 3.56 g cm^{-3} was settled down at 0.7 m sec^{-1} velocity, meaning that lower particle density would exert much lower settling velocity. In general, particle settling velocity increases as long as particle density increase and this was also found to be crucial to the particle shape and size. Ozbayoglu *et al*. (2004) agreed that due to the gravitational effect, greater particle density is harder to be lift.

Effect of Particle size: To examine the particle size effect, the settling behavior was encountered at intermediate fluid viscosity K= 0.2088 Pa.s^n, n = 0.61. Figure 6, shows the settling results for different four particle sizes which flow at low fluid density 0.9982 g cm^{-3}.

It can be observed that, high particle size having more regular shape was behaved high settling. At high fluid density of 1.4379 g cm^{-3}, result of the all size were in low settling behavior compared to their behavior at lower fluid density of 0.9982 g cm^{-3}, as shown in Fig. 7. Thus, such increase on the fluid density from 0.9982 to 1.4379 g cm^{-3} was capable to suspend larger cutting and reduces the settling behavior. The settling velocity of high size particle 0.7 cm and 0.9 shape factor was reduced from 17.98 to 6.44 cm sec^{-1}.

Moreover, flow of small size particle of 0.076 cm at low fluid density was low. Small size has lower settling

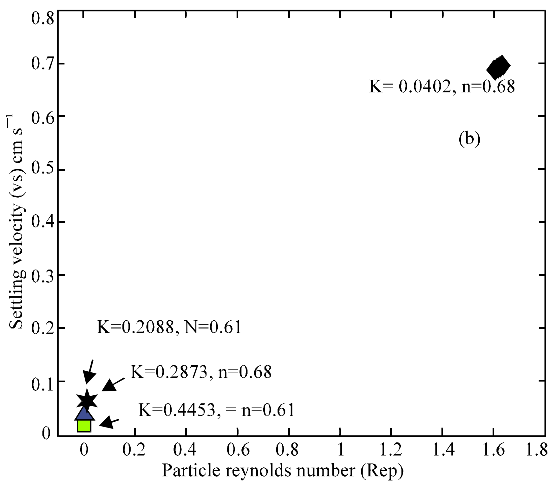

Fig. 10: Effect of the fluid rheology on settling behavior of large particle size

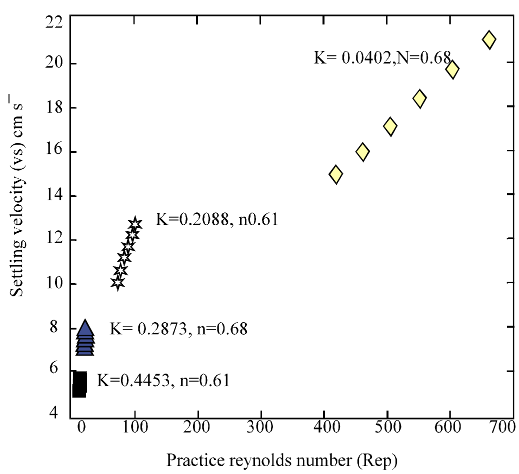

Fig. 11: Effect of the fluid rheology on settling behavior of small particle size

velocity even at high sphericity factor 0.9 compared to the large sized particles which has a significant settling velocity of 17.98 cm sec^{-1}. Large sized cuttings found to behave more settling, (Zhou, 2008) observed that larger cuttings cleaning are the most difficult. On the other hand (Ozbayoglu *et al*., 2004) announced that contribution of the cutting size effect depend on the direction of the fluid flow. As fluid flow vertically prevention of small size settling was the easy.

Effect of fluid density: To inspect the effect of fluid density, medium particle size of 0.4445 cm mean diameter and relatively medium particle density 1.75g cm^{-3} were used. Maintaining the power law fluid viscosity at K= 0.0402 Pa.s^n, n = 0.68, Fig. 8 demonstrated that, the particle settling velocities were high at low fluid density. The lowest settling velocity was encountered at higher fluid density of 1.4379 g cm^{-3}, where 0.75 of particle sphericity was found to settle at 6.84 cm sec^{-1} . While at low fluid density of 0.9982 g cm^{-3}, similar particle exerted 14.18 cm sec $^{-1}$settling velocity.

In Fig. 9, the fluid viscosity was upgraded to have K= 0.4453Pa.s^n, n = 0.61. It can be realized that, regardless of the particle shape all fluid densities were resulted in less settling velocities. Thus, at low fluid densities increasing of the viscosity would help to reduce the high settling behaviors and vice versa.

This agrees with (Zhou, 2008) where increasing of the fluid density resulted in better hole cleaning, that indicate high fluid density able to prevent high settling behavior. In addition (Ozbayoglu *et al*., 2004) reported that increase of the fluid density allows improving the bouncy effect as low force would be required to perform on the settled cuttings.

Effect of fluid rheology: Figure 10, shows the effect of rheological property. Settling of small particle at the different rheological levels of fluid viscosity was low. Generally the settling behavior increased with decreasing of the fluid viscosity.

Larger regular particles of 0.7 cm fall faster in the lower fluid viscosity K = 0.0402 Pa.s^n, n = 0.68, as shown in Fig. 11. In instance, for large particle with sphericity 0.75, the minimum observed settling velocity was 5.22 cm sec^{-1} which occurred at the lowest fluid viscosity. For large particle, the minimum velocity at sphericity of 0.75 was 14.85 cm sec^{-1} and the maximum velocity was 20.97 cm sec^{-1} for particle of 0.9 sphericity. The results shown that, the shape factor was a significant parameter in the settling. As the particle shape approaches spherical shape, the setting rapidly increased. This referred to the reduction of the drag force acting opposite to the settling direction.

Increase in K value from 0.2088 to 0.4453 Pa.s^n reduces the settling velocity for large particle 0.7cm dia. at maximum sphericity 0.9 from 12.65 to 5.65 cm sec^{-1}. Such increasing on K from 0.0402 to 0.2873 Pa.s^n improved the viscosity and served to avoid settling of particle from 20.97 cm sec^{-1} to 7.96 cm sec^{-1} and also reduced Re_p. Thus, particle exerts high Rep at maximum settling velocity. Generally, slight increasing of the fluid viscosity helped to suspend the particle.

Ozbayoglu *et al*. (2004) denoted that increase on the fluid viscosity improves the fluid carrying capacity. Also they reported that reducing of the index behavior n increase the flow velocity and thereby decrease cutting bed's height i.e., resist settling behavior. Besides, (Adari *et al*., 2000) stated that removal of stilled cuttings on bed enhance as n/K ratio increases notice that their above recommendation made to meet highly inclined to horizontal flow direction.

CONCLUSION

The solid in non Newtonian setting was studied. Various fluid and solid properties were considered and their contributions in the settling phenomena were analyzed. It was found that:

- The particle settling behavior is affected by particle shape. With higher shape factor near to sphere, transport process of solid particles in non Newtonian fluids would face faster settling behaviors.
- Higher particle diameter sizes and density with more regular shape near to sphere strengthen the particles settling behavior.
- Increase in fluid density results in noticeable reduction of particle settling velocity especially at high fluid viscosity and small particle sizes. Large particle sizes resulted in higher settling velocities.

The largest effect on the particle settling is achieved at high fluids viscosity. As the fluid viscosity increases the particle settling becomes weaker, even for large size with high particles sphericity. Therefore, it is recommended that transportation fluids should be designed with a higher consistency index K in order to increase the fluid viscosity and thereby overcome the settling behavior. Notice that incase of horizontal transport lower viscosity was recommended to balance between turbulence and suspending capacity of the carrier fluid, (Cho, 2001).

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