



Norwegian University of
Science and Technology

Improving The Efficiency Of Transportation Of Cuttings In Wellbore

Experimental Investigations On Critical
Rolling And Lifting Velocities

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Abstract

Wellbore cleaning is a very important factor during drilling operation as it poses a big challenge and drilling problems, ranging from formation fracture to pipe stuck issues. Drillers have often been tasked by finding the optimum drilling and rheological parameters for proper hole cleaning. Enormous breakthrough and improvement on hole cleaning has been observed in the oil and gas industry, thanks to past decades of efforts channeled through research and studies on the understanding of hole cleaning. Nevertheless, hole cleaning still pose a big challenge in many wells today, mostly as a result of non-compliance on use of optimum drilling and rheological parameters, as well as uncertainty of formation type drilled.

Although significant amount of works and time have been devoted on hole cleaning by different authors, not so much resources have been dedicated to the critical velocities controlling mode of cuttings transport in wellbore. This thesis work focuses on improving the efficiency of transportation of cuttings in wellbore, with major emphasis on the critical velocities of transportation of particles. A literature review on hole cleaning and critical velocities was carried out by the author. Factors affecting hole cleaning and critical velocities of transportation of cuttings was also highlighted in this work. The author reviewed different models for calculating critical rolling and lifting velocities. Analyses of selected model were performed prior to starting the experimental work. Experimental work on critical velocities was performed on a flow loop and the results of the experiments were compared with the theoretical results. From the analyses, the author concluded that the theoretical model could be improved by taking into account plastic forces acting on cuttings particles.

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1. Introduction

During drilling operations, poor hole cleaning may result in slow rate of penetration (ROP), excessive torque and drag, excessive wear on bit, pipe sticking problems, and possibly fracturing of formation, etc. The effects of poor hole cleaning are non-productive time (NPT). Hole cleaning in highly deviated or horizontal wells are more complicated than in vertical holes. High angle wells, with its increased performance and deliverability have its own down side with regards to hole cleaning operations. Poor hole cleaning have dire consequences and as a result, special efforts and considerations are planned in drilling operations to avoid complications or hole cleaning issues.

Many studies on hole cleaning has been carried out by different scientists and researchers over the past decades. The numbers of highly deviated and horizontal wells have increased significantly as a result of improved related knowledge and technology. Integration of optimum drilling fluid properties, and implementation of best drilling practices is necessary for good hole cleaning. As a result, hydraulic simulation or experimental work of wellbore cleaning in drilling operation is highly recommended prior to drilling. For adequate hole cleaning, drilling fluid is expected to possess such rheological properties that can efficiently transport cuttings to surface. And as such, the cutting carrying index, which is a function of drilling fluid, is used as simple tool to determine the efficiency of hole cleaning in drilling operations. Of the various methods proposed by different authors, there has not been an official and globally accepted model for hole cleaning in oil and gas industry, due to complexity of various factors involved in drilling operations ranging from controllable and uncontrollable factors.

The objective of this work is to improve the efficiency of hole cleaning in drilling operation. The approaches adopted for this task involves in-depth study of earlier works on transportation of cuttings, determining the critical velocity of transportation of cuttings from earlier works, and experimental investigation of the critical velocities (rolling and lifting). Evaluating the theoretical results with the results obtained experimentally, will help provide better understanding and improvement on hole cleaning operations.

2. Previous work on hole cleaning

A lot of models have been proposed by different authors for efficient hole cleaning. Moore's correlation (*Moore, 1974*) brought about an interesting model for finding the slip velocity of cuttings in vertical wells. The model focuses on the principle of overcoming slip velocity of cuttings. This model of hole cleaning is not very applicable for high angle wells or horizontal wells. In deviated or horizontal holes, particle's radial slips distance decreases, causing cuttings to settle at the low side of the borehole. This factor, coupled with eccentricity of the drill string makes it difficult to control some of the drilling and rheological parameters in the field. Larson's model (*Larson, 1993*) is aimed at predicting minimum flow rate for cuttings transportation from 55° to 90° degrees of inclination. *Adari et al., (2000)* developed empirical models to correlate the cuttings bed height and hole-cleaning time to drilling properties and corresponding flow rates for high inclination wells. A table summary of previous works on hole cleaning is presented in appendix A.

Prior to visiting various factors affecting hole cleaning, a review of hole cleaning mechanism in different sections of the wellbore with varying angle of inclination, is deemed necessary for adequate understanding of hole cleaning in general.

2.1. Transportation of cutting to the Surface

Two of the major concerns in hole cleaning operation are ensuring that the mud has the right capabilities to clean and transport cuttings from the annulus to the surface, and also ensuring best/recommended drilling practices are implemented at all times. The first part implies that the drilling mud must have the right rheology for efficient transportation of cuttings to the surface. The types of flow and rheology models are given in appendix B. Methods and models for wellbore cleaning varies for different hole angle of inclination. In hole cleaning process, the wellbore can be divided into 3 sections: low inclination (>30°), Medium inclination (30°-65°) and high inclination (>65°) section.

2.1.1. Hole cleaning in low inclination wells (< 30° Inclination)

Removal of cuttings in vertical wells is a lot easier to control than in high deviated or horizontal wells. A vertical well may be classified as a wellbore with less than 10° inclination angle. Wellbore sections with inclination angle of 10° -30° can be classified as low inclination sections or wellbore. Basically, the three major factors affecting hole cleaning in vertical wells are the annular velocity, cuttings slip velocity, and viscosity of fluid.

For the vertical wells, hole cleaning principle is based mainly on overcoming slip velocity of cuttings, while encompassing sufficient annular velocity and cuttings carrying capacity in the drilling fluid program. In other words, it assumes that any fluid velocity greater than the settling velocity of the largest cuttings will eventually lift the all the cuttings to the surface (*Harvey, 1990*). High viscous mud provides better transportation of cuttings in low inclination wells than mud with low viscosity. The theories of slip velocity and effect on hole cleaning in vertical section of the well is given in appendix B.

For vertical wells, laminar flow regime is preferred to turbulent flow regime so as to avoid washout, ensuring the drilling fluid and annular velocity is sufficient to transport and suspend cuttings to surface.

2.1.2. Hole cleaning in medium inclined wells (30° to 65°)

As the hole inclination increases, particles' radial slip increases, thereby increasing the tendency for particles to settle at low side of the well. Critical angle can be found in this section. Cutting bed tends to develop in this section, and this unstable bed is prone to sliding backward (avalanching), which could lead to stuck pipe. The poorest removal rates generally occur with angles in the region of 50 to 60 degrees (*Brown et al., 1989*). Also in such inclined well, when the drilling fluid contains high concentration of barite (relatively high density), there is likelihood of barite segregation in hole. The sagging of barite, when the gelled mud's yield point is exceeded, forms a stratified layer of barite and cuttings, which adversely affects hole cleaning.

Here the effect of turbulent or laminar flow has little or no effect for hole cleaning in this section, however many researchers believe turbulent flow regime is preferable at this section as they tend to erode cuttings bed. Pipe rotation is highly recommended in this section, as it helps to stir and reduce cuttings bed height.

2.1.3. Hole cleaning in highly inclined wells (65° to 90°)

Majority of wells drilled in last decades have mostly been directional wells as a result of its economic benefits and improved technology in the industry. Horizontal wells are more associated with hole cleaning problem. Hole cleaning is much more complicated in horizontal wells compared to the other afore mentioned regimes. The well trajectory makes it more difficult to remove cuttings from the horizontal section of the well. The mud Engineer is usually faced with challenges of wellbore stability and cuttings removal in horizontal well. In horizontal wells, the vertical component of mud velocity is reduced, and as a result, the cuttings suspension capability of the mud is reduced. This leads to increase probability of cuttings settling on low side of the well.

Turbulent flow regime is highly recommended in this section as turbulent flow helps to disturb and reduce cutting bed height.

2.2. Review of factors affecting hole cleaning

Factors affecting hole cleaning can be divided into 3 groups. The first group consists of fluid parameters which include; fluid viscosity, fluid density, and fluid flow rate. The second group consists of cuttings parameters which include; cutting density, size and shape, and cutting concentration in the annulus. The third group consists of pipe rotation, and eccentricity in the hole (*Belavadi & Chukwu, 1994*).

Adari et al., (2010), listed some of the elements affecting hole cleaning, by ranking them based on its importance and influence on hole cleaning, presented in figure 2.1.

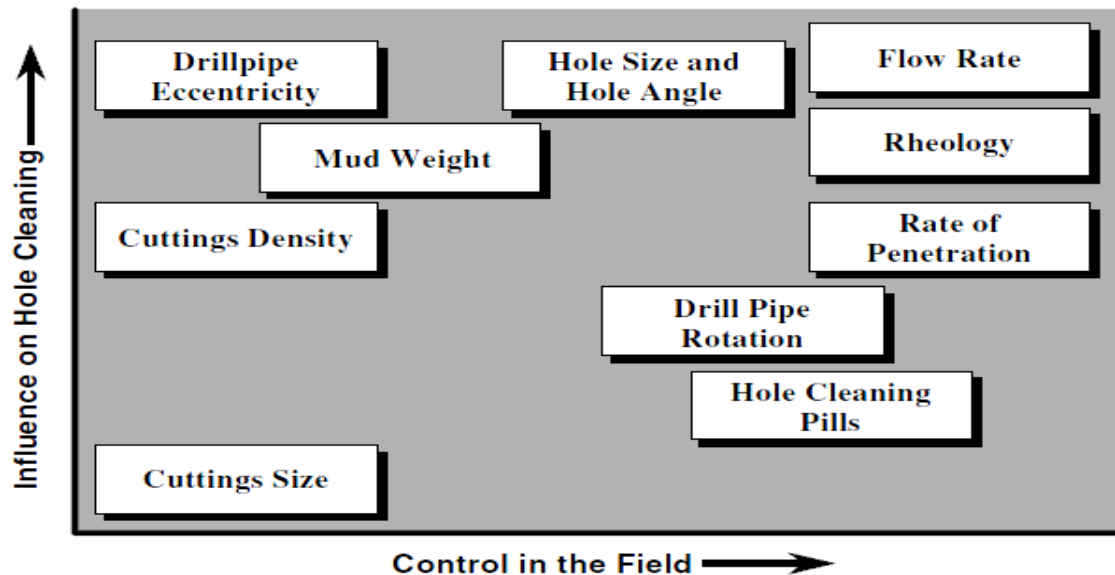


Figure 2.1: Key variables controlling cuttings transport (*Adari et al., 2000*)

2.2.1. Effect of drilling parameters

2.2.1.1. Hole inclination

Previous work from various authors showed that wellbore inclination affects hole cleaning significantly. It has been established that hole cleaning in directional or horizontal well is more complicated than in vertical wells. As the inclination increases, radial component of the cuttings slip velocity gradually increases. *Tomren et al., (1986)* performed an experimental study of cuttings transport in directional well, where the wellbore inclination was varied (0° - 90°), they observed that the effective flow area was reduced by a growing formation cuttings bed at high

liquids rates for angles that were greater than 40° degrees. The Authors concluded that angles between 35° and 55° degrees were critical angles since they caused bed forming and a bed sliding downwards against the flow. *Okranji and Azar (1986)* stated that increase in the hole inclination will lead to decrease radial component of the slip distance, and subsequently leads to more cuttings settling at low side of the wellbore. *Sifferman and Becker (1992)* argued that that beds forming at inclination angles between 45° and 60° degrees might slide or tumble down, while cuttings bed was less movable at inclination between 60° to 90°. *Li and Walker (2001)* argued that the most challenging section for hole cleaning is the “build” section, not the vertical nor the horizontal sections. It was observed that increasing the inclination angle resulted in higher cuttings bed. The authors also stated that hole cleaning is most difficult at approximately 60° inclination of wellbore.

2.2.1.2. Pipe rotation (RPM)

Pipe rotation is known to help significantly improve hole cleaning. The effect of RPM is more noticeable in deviated holes. *Sanchez et al., (1999)* revealed that pipe rotation has significant effect on hole cleaning in directional well. It was observed that a low flow rate with high RPM significantly improved hole cleaning in horizontal wells. The Authors stated that smaller cuttings were more difficult to remove from wellbore. However, with a high RPM and high viscosity of mud, it was easier to transport smaller cuttings to surface.

When the pipe is rotated, tangential velocity in the fluid is initiated across the annulus gap, starting next to the casing. This leads to the transfer of fluid from the wide side to the narrow side, and vice versa (*Moroni et al., 2009*). The pipe rotation helps to create a turbulent like flow in the high inclination section of the well, thereby leading to more reduction of cuttings bed height in the narrow end of the well. Figure 2.2 shows the effect of rpm on hole cleaning in high angle wells.

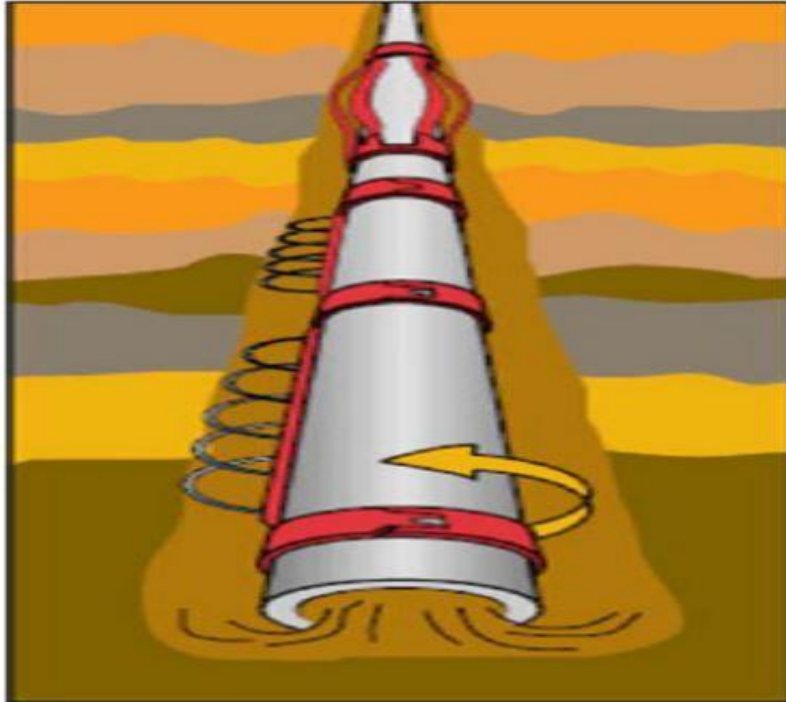


Figure 2.2: Pipe rotation helps fluid flow in the narrow side of an eccentric annulus (*Moroni et al., 2009*)

The viscous coupling effect between mud and drill pipe helps to create a conveyor belt that helps to transport cuttings to surface. The effect of RPM is also observed to be dependent on pipe to hole area ratio (P-HAR). This P-HAR is used with the graph figure 2.3 to show optimum and efficient RPM recommendation for good hole cleaning.

$$\frac{D_{hole}^2}{D_{pipe}^2} = \text{P-HAR} \quad (1)$$

For P-HAR more than 3.25, curve for large diameter is used.

For P-HAR less than 3.25, curve for small diameter is used.

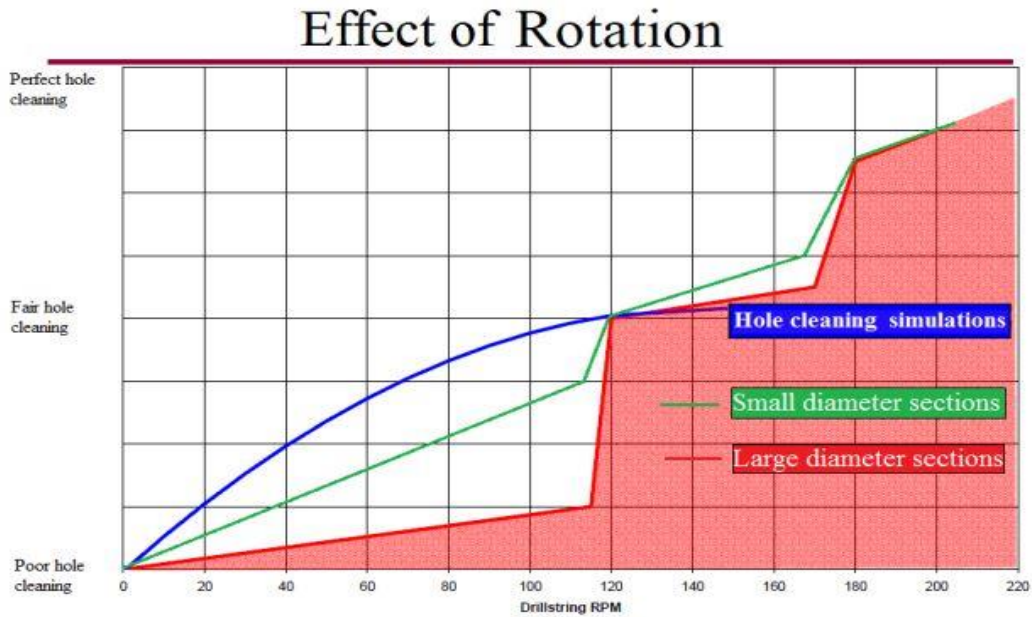


Figure 2.3: RPM selection for hole cleaning based on P-HAR (Brechan, 2015)

2.2.1.3. Rate of penetration (ROP)

Increase in ROP tends to increase or generate more cuttings which adversely affects hole cleaning. The more the cuttings, the higher the required hydraulic output required for efficient hole cleaning. When ROP is high, it is recommended to adjust flow rate and/or RPM for good hole cleaning. When the effect of flow rate and RPM is exhausted, it is recommended to reduce ROP. Though reduction in ROP can lead to drilling cost, the benefits of avoiding drilling/hole cleaning issues such as mechanical sticking and stuck pipe, outweighs the loss in ROP.

2.2.1.4. Eccentricity

Effect of eccentricity has been investigated by various authors. Eccentricity is usually prominent in highly deviated wells. In the inclined section of the well, the pipe tends to rest on the low side of the wellbore as a result of gravity. A simple sketch of eccentricity of drill pipe in hole is shown in figure 2.4.

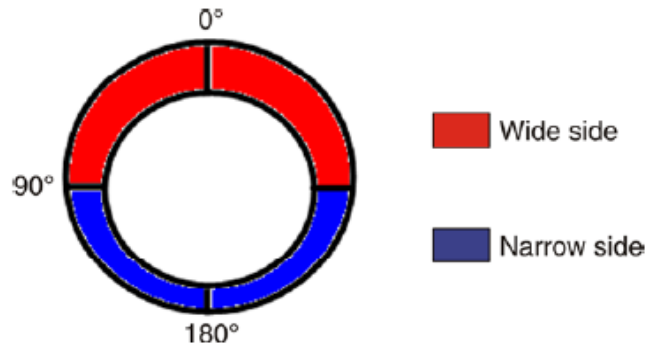


Figure 2.4: Illustration of wide and narrow sides in an eccentric annulus (*Moroni et al., 2009*)

This phenomenon creates a narrow gap between the pipe and the annulus on the low side of the well, thereby causing restriction to the flow velocity of the mud. *Iyolo and Azar (1981)* revealed the effect of eccentricity on hole cleaning, as they observed low annular velocity at low side of the drill pipe as result of eccentricity. The drilling fluid profile in laminar flow regime as shown in figure 2.5, created by the eccentricity of drill pipe, affects the efficiency of wellbore cleaning. The effect of drill string sagging at low side of the well, leads to increase in cutting bed height, due to obstruction on annular velocity on the low side of the well.

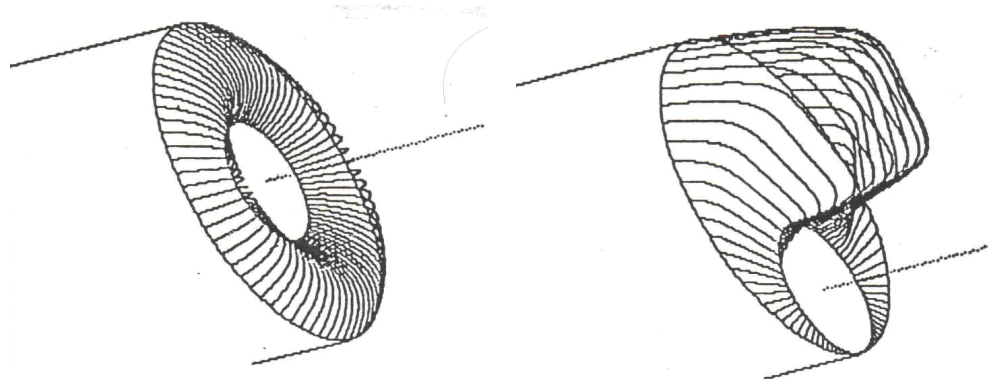


Figure 2.5: Effect of eccentricity of drill pipe on velocity profile of drilling fluid in horizontal wells (*Habibullin 2008*)

2.2.2. Effect of fluid parameters on transportation of cuttings

2.2.2.1. Mud Weight

The two major fluid parameters affecting hole cleaning are mud weight and viscosity. The mud weight primarily provides mechanical borehole stabilization and prevention of invasion of

formation fluid into the annulus. In hole cleaning, drilling fluid mud weight has little or no effect on hole cleaning. However, a small increase in mud density decreases bed height (*Nazari et al., 2010*). Increasing drilling fluid density with same rheology has little or no effect on hole cleaning. Any unnecessary increase in mud weight could lead to formation fracture.

2.2.2.2. Mud type

Mud type has also been established by different authors to have small to moderate effect on hole cleaning. Oil base mud and water based mud with the same rheology are generally the same in terms of hole cleaning capacity. For inclination range of 40 to 60 degrees, water based mud performs slightly better than oil based mud, in hole cleaning. However, water based mud could lead to a number of problems especially when drilling through reactive shale, which could lead to hole stability problem.

2.2.2.3. Mud rheology

Mud Rheology is a primary function of the plastic viscosity (PV) and its yield point (YP). Mud rheology has significant effect on hole cleaning. The PV and YP are calculated from FANN reading at 300 RPM and 600 RPM. Increase in PV and YP tends to improve hole cleaning.

It has been observed that increasing the viscosity of mud has positive impact on hole cleaning, and particularly effective if the low shear rheology and YP/PV ratio are high. However too much increase of mud viscosity (above optimum viscosity) is observed to have negative effect on hole cleaning. It is also known that increasing fluid viscosity at same flow rate turns the current turbulent regime to laminar flow, which has less cleaning ability in high angle wells (*Piroozian et al., 2012*).

2.2.2.4. Flow rate

The mud flow rate provides the lifting force on cuttings for transportation of cuttings out of the well. Increasing the flow rate helps immensely in hole cleaning. According to majority of authors, increasing the flow rate is necessary for reduction of cutting bed height.

Increase in annular velocity of drilling fluid helps in efficient hole cleaning. The effect is more prominent in high inclination wells. The following guideline for annular velocity has been established (*Brechan et al., 2015*):

- 1 m/s – Ideal hole cleaning.
- 0.75 m/s – Minimum required hole cleaning.

- 0.5 m/s – Poor hole cleaning and possibly barite sag in deviated sections.

2.2.3. Effect of cuttings parameters

Hole cleaning can also be affected by cuttings size, shape and density, to a certain degree. Increase in both cutting size and density, tends to increase slip velocity, which adversely affects hole cleaning as result of more cuttings settling and increasing cuttings bed height. Part of the experimental work on the effect of cuttings density on pump rate was conducted by *Habibullin (2008)* using sand of density 2300kg/m^3 and proppant of density 3100 kg/m^3 on different fluids, is presented in Figure 2.6.

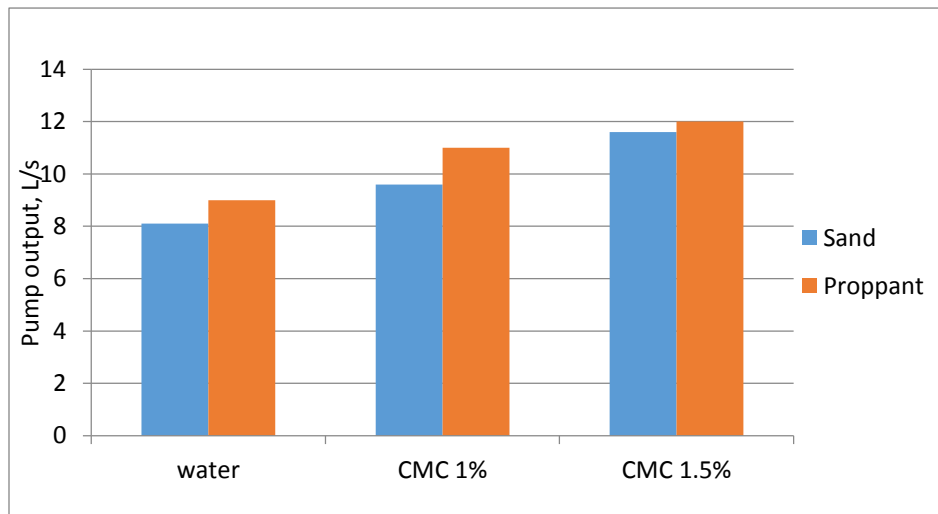


Figure 2.6: Effect of cuttings density on pump rate for various fluid of different viscosity (*Habibullin 2008*)

From figure 2.8 above, it is evident that proppant, which has higher density than sand requires more pump out or increased flow rate so as to transport the particles out of the channel. This entails that particles with higher density requires increased annular velocity for efficient hole cleaning.

Cuttings size slightly influences hole cleaning. According work of Larson, small particles are more difficult to clean than larger particles especially when the cuttings size is larger than 0.5in. This is because the smaller particles form more compact bedding compared to the bigger particles that form loose cutting bed that can easily be swept away. For particles size less than 0.5in, smaller cuttings size is easier to clean than larger size (*Walker et al., 2000*). The more

spherical shape cutting in the hole, the faster it will fall down. The shape of cuttings also affects efficiency of hole cleaning. Spherically shaped cuttings tend to slip more to settle at lower side of the well. The higher the cuttings concentration, the higher the ECD, the higher the probability of hole cleaning issues.

2.3. Previous work on critical velocity

Research on critical fluid velocity necessary to initiate motion of particles has been investigated by many scientists and researchers. Some of the prominent work on fluid critical velocity will be discussed in this chapter.

2.3.1. Forces acting on cutting particles

Analyzing the forces that are involved in motion of particle is necessary for sufficient understanding of cuttings transport in wellbore. Therefore, the forces acting on a particle should be studied before determining its motion state (*Zhang et al., 2013*).

In a horizontal open flow channel, the forces acting on bed-load particle are : a downward force due to its submerged weight (F_w) and hydrodynamic fluid forces, which can be resolved into a lift force (F_L), and a drag force (F_D) (*Van Rijn, 1984*). This classification however did not include the inter-particle forces (F_P) acting between the sediment particles. *Duan et al., (2009)* took into consideration inter-particle forces in their work. The authors classified the forces acting on a particle on a solid bed into three groups: the static forces (Gravity and buoyancy forces) which are due to the properties of the particles and its surrounding fluid; the hydrodynamic forces (drag and lift forces) due to fluid flow; and the inter-particle forces (Van der waals forces) due inter-particle forces (F_P) existing between any neighboring particles. Plastic force, which is due to the gel strength of the fluid, is only considered when a particle is stationary on the surface of the bed (*Ramadan et al., 2003*).

A schematic diagram of all the forces acting on a single bed particle is shown in figure 2.7. According to the mechanistic model, the net lifting force or net rotating torque acting on a single bed particle determines the state of motion of the particle. A positive value of the net lift force or the net rotating torque is required to displace a bed particle (*Ramadan et al., 2003*).

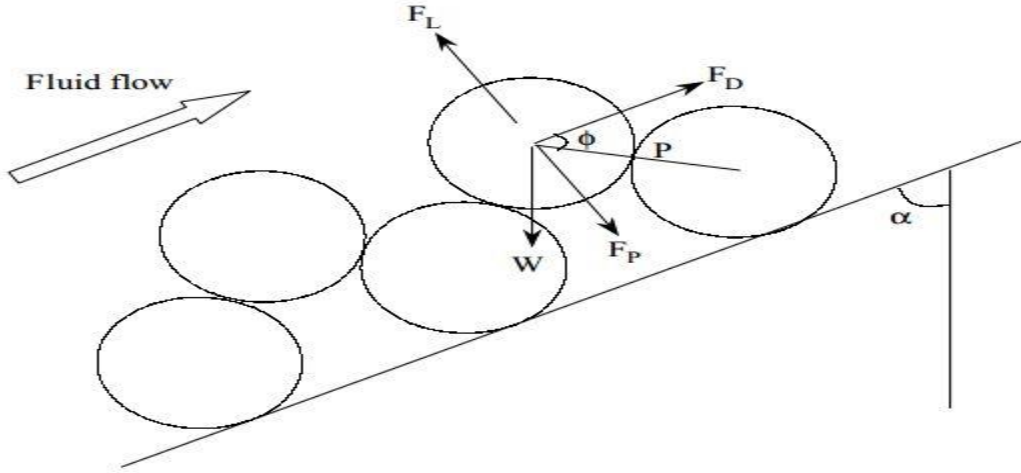


Figure 2.7: Forces acting on a single bed particle (*Ramadan et al., 2003*)

The difference between the gravitational force and buoyancy force that act on particle sediments submerged in fluid is referred to as net weight (F_w). The submerged particle weight was expressed by *Van Rijn* as:

$$F_w = \frac{1}{6} \pi D^3 (\rho_p - \rho_f) g \quad (2)$$

Drag and lift forces are experienced when a body moves relative to its surrounding fluid. These forces are as a result of pressure and shear stress that can be obtained by integration of pressure and shear stress across the surface of a particle as seen in figure 2.8. When there is relative movement between the particle and its surrounding fluid, the particle will experience a drag force induced by pressure and shear stress acting on the particle surface (*Landau and Lifshitz 1986*). Drag force can be expressed as (*Zhang et al., 2013*):

$$F_D = \frac{1}{8} \pi C_D \rho d_p^2 v_r^2 \quad (3)$$

C_D = drag coefficient, ρ = fluid density, v_r = particle velocity relative to flow, $d_p = 2R$ is the diameter of cuttings.

The drag coefficient C_D , which is a function of geometry and size of bed particles, was presented by *White (1991)* as

$$C_D = \frac{24}{Re_p} + \frac{6}{1+Re_p^{0.5}} + 0.4 \quad (4)$$

The expression of drag coefficient above is only valid for single particle without the presence of neighboring particles. Therefore it is relevant to account for variation of drag coefficient due to presence of other neighboring particles on surface of a solid rock. *Ramadan et al., (2003)* introduced the term drag ratio (D_R), into the Drag force equation.

A different approach was taken by *Turton & Levenspiel (1986)* in defining the C_D , taking into account the effect of other neighboring particles, as shown in equation (4*) below:

$$C_D = \frac{24(1+0.173Re^{0.657})}{Re} + \frac{0.413}{1+16300Re^{-1.09}}, \text{Re} < 2 \times 10^5 \quad (4^*)$$

The lift force (F_L) which is caused by velocity gradient present in the flow (shear effect) and by spinning motion of the particle is expressed as (*Saffman 1965*):

$$F_L(\text{shear}) = \alpha_L \rho v^{0.5} D^2 v_r \left(\frac{\partial u}{\partial z}\right)^{0.5} \quad (5)$$

where α_L = lift coefficient, v =kinematic viscosity coefficient, D = particle size, $\frac{\partial u}{\partial z}$ = velocity gradient.

The above lift force equation is only valid for small Reynolds' numbers. *Rubinow and Keller (1961)* expressed the lift force due to spinning motion of viscous flow as:

$$F_L(\text{spin}) = \alpha_L \rho D^3 v_r w \quad (6)$$

where α_L = lift coefficient (=0.4 for viscous flow), w = angular velocity of the particle.

The lift force correlation proposed by *Saffman* cannot be used for particles on or near a surface, as it is only valid for particles transportation in no boundary. Hence, *Clark and Bickman (1994)* proposed that the lift force correlation could be calculated with

$$F_L = C_L \pi \rho_f d_p^2 u_r^2 / 8 \quad (7)$$

$C_L = \text{Lift coefficient} = 0.178 = 5.82(\alpha_p/\text{Re}_p)^{1/2}$; and $\alpha_p = \frac{d_p}{2u} \left| \frac{du}{dr} \right|$; u_r is the relative fluid-particle velocity; d_p is the diameter of cuttings; ρ_f is the density of the fluid.

Having identified the forces acting on bed particle, it is paramount to understand how these forces affect the motion of particles.

2.3.2. Mechanism and types of particle motion

Transportation of cuttings in wellbore assumes different forms. *Bagnold (1973)* in his early works on transportation of particles in channels, defined bed load as that in which the successive contacts of particle with the bed are strictly limited by the effect of gravity, while the suspended load transport is defined as that in which the excess weight of the particles is suspended wholly by a random succession of upward impulses imparted by turbulent eddies. *Van Rijn (1984)* classified form of transportation of sediment particles into 2 groups: bed-load and suspended load. The author went further to distinguish 3 forms of particle motion: Rolling and sliding motion or both; saltation motion; and suspended particle motion. The rolling and sliding or both motions is observed when the values of the bed-shear velocity just exceed the critical value for initiation of motion. Further increase in the values of the bed-shear velocity will result in the particles moving along the bed by more or less regular jumps, known as saltation. Suspension of particles is observed when the value of the bed-shear velocity exceeds the fall (slip) velocity of the particles, where the sediment particles are lifted up as a result of turbulent force equal or exceed the submerged weight of the particles.

Based on literature review, the velocity necessary to initiate particle motion can be classified into critical rolling velocity and lifting velocity.

2.3.2.1. Critical rolling velocity

The study of the minimum velocities at which cuttings begins to move, is considered very important for proper understanding of hole cleaning and drilling fluid hydraulics. It has been observed by different authors that rolling transportation of cuttings-bed particles exist in directional wells, particularly at high inclination angles, as particles will tend to roll and bounce along the bed surface.

Van Rijn (1984), in his work proposed using *Shields* curve to obtain critical bed-load velocity for flow in open channel. The author argued that the bed-load transport rate can be described sufficiently accurate by two dimensionless parameters namely: particle parameter (D_*), and transport stage parameter (T). The particle and transport stage parameters are expressed as:

$$\text{Particle parameter, } D_* = D_{50} \left[\frac{(s-1)g}{\nu^2} \right]^{\frac{1}{3}} \quad (8)$$

where

D_{50} - particle size; s - specific density (ρ_s / ρ); g - acceleration of gravity, ν - kinematic viscosity coefficient

$$\text{Transport stage parameter, } T = \frac{(u_*')^2 - (u_{*,cr})^2}{(u_{*,cr})^2} \quad (9)$$

where

$u_*' = (g^{0.5}/C') \check{u}$ - bed-shear velocity related to grains; C' - Chezy-coefficient related to grains; \check{u} - mean flow velocity; $u_{*,cr}$ - critical bed-shear velocity according to *Shields (1936)* as shown in graphical form in Figure 2.8.

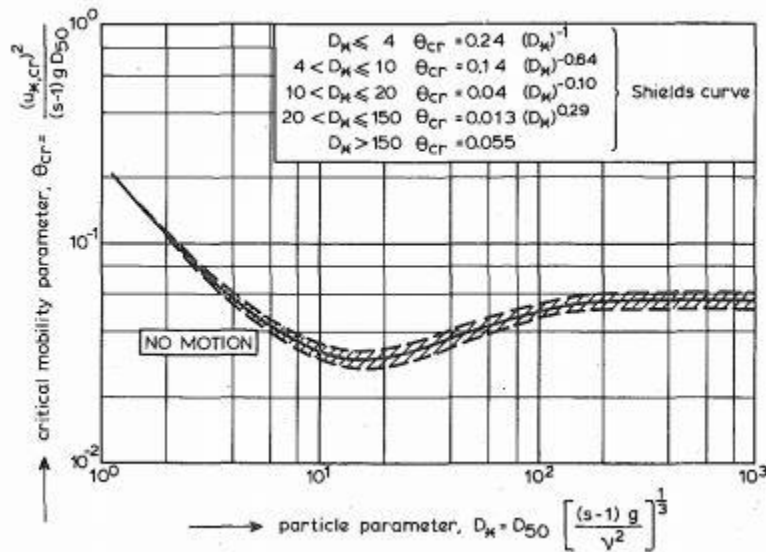


Figure 2.8: Initiation of Motion according to Shields (*Van Rijn 1984*)

In directional wells, a more recent approach has been presented by various authors. *Zhang et al., (2013)* presented the minimum rolling transport velocity of bed-load particle as

$$u_{roll} = \left(\frac{4d_p g (s-1) \sin(\phi + \alpha)}{3(0.8C_D \sin \phi + C_L \cos \phi)} \right)^{0.5} \quad (10)$$

where

$s = \rho_p / \rho_f$; ϕ = angle of repose; α = angle of inclination

Taking into account the plastic force due to gel strength of fluid, Ramadan et al., (2003) presented formulas for calculating the critical rolling velocity of cuttings particle as follow

$$u_{roll} = \left(\frac{6 \tau_y \cos \phi + 4 d_p g (s-1) \sin(\phi + \alpha)}{3(D_R C_D \sin \phi + C_L \cos \phi)} \right)^{0.5} \quad (11)$$

where

τ_y - Yield stress of the fluid; D_R - Drag ratio.

2.3.2.2. Critical lifting velocity

Before determining the lifting or suspension transport velocity of particles, it is important to understand the flow regime at which initiation of suspension will most likely to occur. *Bagnold (1966)* stated that a particle will only remain in suspension in turbulent flow when the dominant vertical velocity components (w') exceeds the particle fall velocity (w_s). The turbulence intensity (\hat{w}), which is critical value for initiation for initiation of suspension, can be expressed as:

$$\hat{w} = [(w')^2]^{0.5} \geq w_s \quad (12)$$

Research suggests that the maximum value of vertical turbulence intensity is equal to the bed shear velocity. The critical bed shear velocity ($u_{*,crs}$) for initiation of suspension can then be expressed as:

$$\frac{u_{*,crs}}{w_s} = 1 \quad (13)$$

This can also be rewritten in the form below (from figure 2.9)

$$\theta_{crs} = \frac{(u_{*,crs})^2}{(s-1)gD_{50}} = \frac{(w_s)^2}{(s-1)gD_{50}} \quad (14)$$

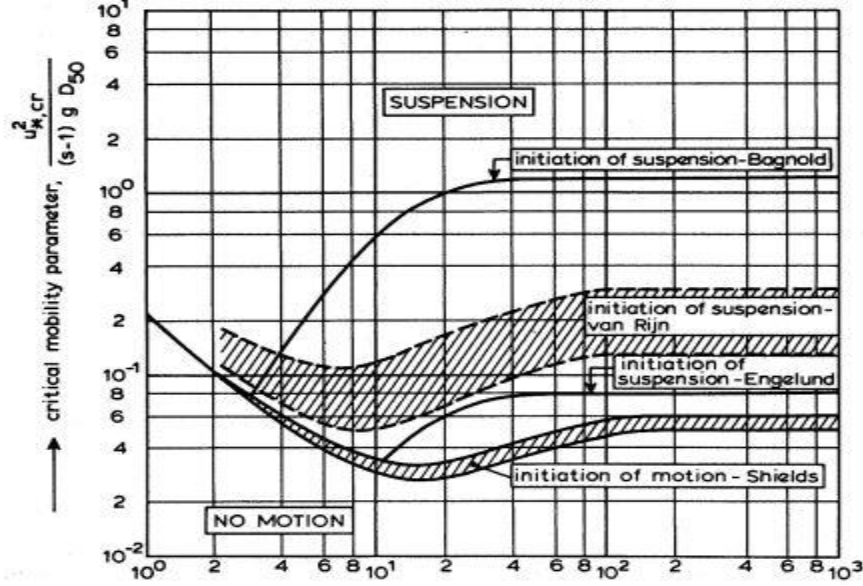


Figure 2.9: Initiation of motion and suspension (*Van Rijn 1986*)

Engelund (1965) proposed a different criterion for initiation of suspension of particles based on crude stability analyses as:

$$\frac{u_{*,crs}}{w_s} = 0.25 \quad (15)$$

Zhang et al., (2013) stated that, on increasing the fluid flow rate to a certain value, the particles on bed surface will be suspended and move into suspension transportation. The authors proposed that the minimum suspension velocity expressed in y-x directions can be expressed as shown below respectively:

$$u_{susx} = \left[\frac{4d_p g (s-1) \cos \alpha}{(3C_D)} \right]^{0.5} \quad (16)$$

$$u_{susy} = \left[\frac{4d_p g(s-1) \sin \alpha}{3C_L} \right]^{0.5} \quad (17)$$

A special relationship was observed on analyzing the two equations, as can be seen from the expression below

$$\frac{u_{susy}}{u_{susx}} = \left[\frac{\tan \alpha C_D}{C_L} \right]^{0.5} \quad (18)$$

$$u_{sus} = \max \left| u_{susx}, u_{susy} \right| \quad (19)$$

Garcia-Hernandez et al., (2007) observed that the average cuttings lag was nearly 40% of the fluid velocity in horizontal and deviated wells. Therefore, the critical fluid velocity to guarantee the results of a sand washing project in a horizontal well should be:

$$v_c = v_r / 0.4 \quad (20)$$

where

v_c = critical fluid velocity, v_r = relative velocity of between cuttings and fluid.

Ramadan et al., (2003) considered the effect of plastic force due to gel strength of fluid and proposed that the critical lifting velocity can be estimated using the formula below

$$u_{Lift} = \left(\frac{2\tau_y}{C_L \rho_f} + \frac{4d_p \sin \alpha (s-1)g}{3C_L} \right)^{0.5} \quad (21)$$

Review of these various models for calculating critical velocities was deemed necessary for proper understanding of cuttings transport, and grasping the physics behind these models, which ultimately will help decide which model to choose and test prior to starting the experiments.

3. Selected model analyses of critical velocities

Prior to starting the experiments, the factors affecting the critical lifting and rolling velocities was investigated. The model presented by *Zhang et al., (2013)* for calculating critical velocities was chosen as a base case for our analyses. The Zhang's model implored using Turton's formula for calculating the drag coefficient when determining the critical rolling velocity. The lift coefficient was taken as a function of particles Reynolds number, particle size and shear rate. One of the assumptions of this model was that the fluid was fully developed flow without fluctuations. This assumption fits with the planned experimental work to be presented later in this thesis, since the experimental loop had developing section that allows the flow to stabilize before the cuttings are flushed. Zhang's model, from the table 2.6 did not include plastic forces in calculating the critical velocities. This will be tested in the experiments as two different fluids with varying viscosities will be used for the experiment to be conducted in this work. The model parameters are presented in the table 3.1.

Table 3.1: Model of critical velocities

Parameters	Formulas
Drag coefficient	$C_D = \frac{24(1 + 0.173Re^{0.657})}{Re} + \frac{0.413}{1 + 16300Re^{-1.09}}$
Lift coefficient	$5.82(\alpha_p/Re)^{1/2} = 0.178$
Critical rolling velocity	$u_{roll} = \left(\frac{4d_p g(s-1) \sin(\phi + \alpha)}{3(0.8C_D \sin \phi + C_L \cos \phi)} \right)^{0.5}$
Critical lifting velocity	$u_{lift} = \left[\frac{4d_p g(s-1) \sin \alpha}{(3C_L)} \right]^{0.5}$

The review of effect of particle size, rheology and inclination on the critical velocities using this model was deemed necessary not just to provide insight on potential outcome of the experiment to be conducted, but also to determine or validate if the model is to be trusted. To carry out this investigation, a tentative, but practical data set was used in computing the critical rolling and lifting velocities. For the experimental part of this thesis work, particle size of 1.5 mm will be used and as a result, same particle size was included in the base case for later analyses and comparison of theoretical and experimental results. The data used in this calculation are presented in table 3.2.

Table 3.2: Data implemented in calculating critical velocities

Parameters	τ (Pa)	dp (mm)	ρ_f (kg/m ³)	ρ_p (kg/m ³)	Inclination angle (°)	Repose angle (°)	C _D -	C _L -
value	1.25	1.5	1150	2700	60	20	0.459	0.178

The effect of particle size was investigated by using particles of different diameters to calculate the critical rolling and lifting velocities. Major emphasis will be laid on the inclination of 90° as the planned experiments will be conducted in the horizontal section of the flow loop. Results are presented in table 3.3, and then shown graphically in figure 3.1.

Table 3.3: Computed results of critical velocities on varying the particle size

Particle diameter (m)	Repose angle (°)	Inclination angle (°)	u_{roll} (m/s)		u_{lift} (m/s)	
			water	Plastic fluid	water	Plastic fluid
0.0005	20	60	0.15	0.14	0.23	0.21
0.001	20	60	0.22	0.20	0.33	0.29
0.0015	20	60	0.27	0.24	0.40	0.36
0.002	20	60	0.31	0.27	0.47	0.41
0.003	20	60	0.38	0.34	0.57	0.51

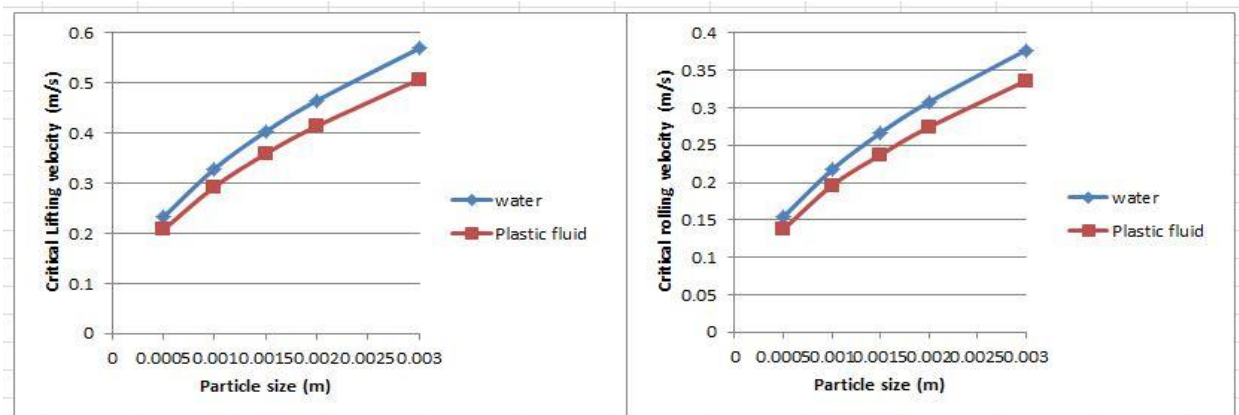


Figure 3.1: Theoretical effect of particle size on critical lifting (left) and rolling (right) velocities

The so called *plastic fluid* in the tables and figures in this work refers to non-Newtonian fluids, which have shear rate, not proportional to shear stress. As can be seen from figure 3.1, increase in particle diameter leads to increase in critical velocities. This implies that increase in cuttings diameter will require an increase in flow rate and annular velocity for efficient hole cleaning. Another important observation is that an increased flow rate is needed to initiate the lifting of particles. The comparison of the two velocities shows that rolling motion of particle is first witnessed, until flow rate is increased to that critical flow, necessary to start the lifting motion of particles. For particle size of 1.5 mm, initial rolling motion in water was recorded at 0.2263 m/s, while initial lifting motion was observed on increasing the fluid velocity to 0.403 m/s.

Effect of inclination was as well investigated by varying the inclination (0, 20, 30, 60, 80, 90), and using sand particle diameter of 0.5 mm. Results are shown in table 3.4.

Table 3.4: Theoretical results of critical velocities on varying the inclination angle

Angle of inclination (°)	u_{roll} (water) (m/s)	u_{roll} (plastic fluid) (m/s)	u_{lift} (water) (m/s)	u_{lift} (plastic fluid) (m/s)
0	0.15	0.14	0.12	0.11
20	0.16	0.15	0.17	0.19
30	0.16	0.15	0.19	0.21
60	0.16	0.15	0.21	0.23
80	0.15	0.14	0.23	0.26
90	0.12	0.10	0.25	0.28

The computed results on effect of inclination on critical rolling and lifting velocities are shown in figure 3.2.

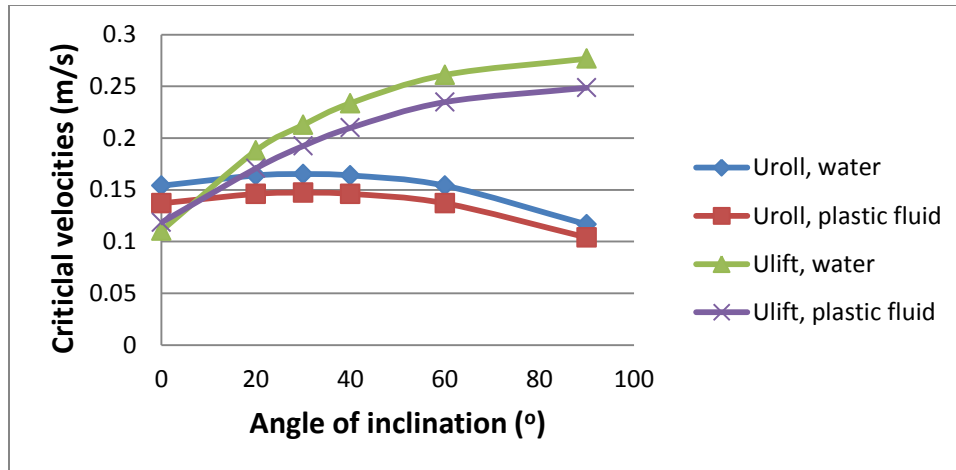


Figure 3.2: Comparison of theoretical effect of inclination on critical rolling and lifting velocities

From figure 3.2 above, lifting motion dominates in vertical/low inclined wells, while rolling motion is dominant in highly inclined wells. In inclined well section, increase in flow rate is required to attain the critical velocity necessary for lifting of cuttings out of the hole. This observation corresponds with the theory as rolling motion is agreed by many author to dominate highly inclined well section, - thus, validating this model for use in the intended experiment.

So far, the model used for calculating the critical rolling and lifting velocities has been corresponding to theoretical aspect of the thesis work. The model used in calculating the critical rolling and lifting velocities has shown to be reliable based on various scenarios tested above. The test showed that increase in particle sizes leads to increase in critical velocities. In high angle well sections, the rolling mode of transportation dominates, while lifting dominates in vertical or low inclined sections of the wellbore. This model, therefore will be implemented for the experimental work, and the results will be analyzed and compared with the theoretical results.

4. Experimental investigation on critical velocities

The aim of this experiment is to determine the critical velocities of cuttings particles and testing the quality of the selected model. The experiment is to be performed by using fluids with varying viscosities. A set of sand particle size of 1.5 mm was used in this experiment and the fluid viscosity was varied using the Xanthan gum. The general principle of the experiment involves flushing different fluid with varying rheology over a set of sand particles in a test loop (simple flume installation). The flow rate is gradually increased until particle motion is initiated. The critical flow rate is then recorded and converted to the critical average velocity. This chapter covers the description of the experimental setup, installation, as well as the results obtained from the experiment. The theoretical and experiment results will be compared and analyzed also in this chapter.

4.1. Test Loop Description

The schematic of the experimental flow loop is shown in the figure 4.1. The *overhead tank (fluid reservoir)*, which gets water supply from the tap, is connected to test section, the horizontal part of the loop, through a *vertical pipe*. The *On/off valve* is located between the overhead tank and the *vertical pipe*. The *On/Off valve* helps to start/shut the gravity aided flowing of fluid from the overhead tank down to the *vertical pipe*. This valve is particularly useful during the mixing of the Xanthan gum with water, as it helps to regulate the volume of water, and calculation of concentration of Xanthan gum, necessary for efficient rheology modification of fluid for the experiment.

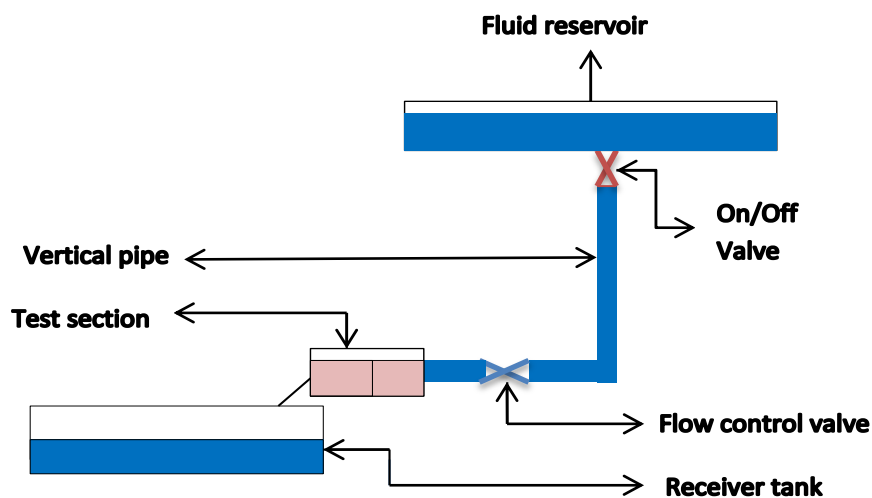


Figure 4.1: Test loop schematics

The *flow control valve*, located at the horizontal section of the loop, acts as a regulator for adjusting flow rates to desired value. An inlet pipe of 4.5 cm extends from the horizontal section of the loop, into a 110 cm *test section*. The *test section*, shown in figure 3.2, is made of transparent glass for observation of flow and particle motion. This section consists of 2 parts - a 60 cm developing section, and a test tray of 50 cm length. The developing section helps to stabilize the flow of fluids before going into the test tray, to enhance qualitative results. The test tray, connected to the developing section is filled with sand particles prior to opening the *flow control valve*. A removable inlet and outlet ramps hold the sand particles in place in the test tray. The fluids and the sand particles from the test section are collected in the *receiver tank* for recycling. The test section of the flow loop is shown in figure 4.2

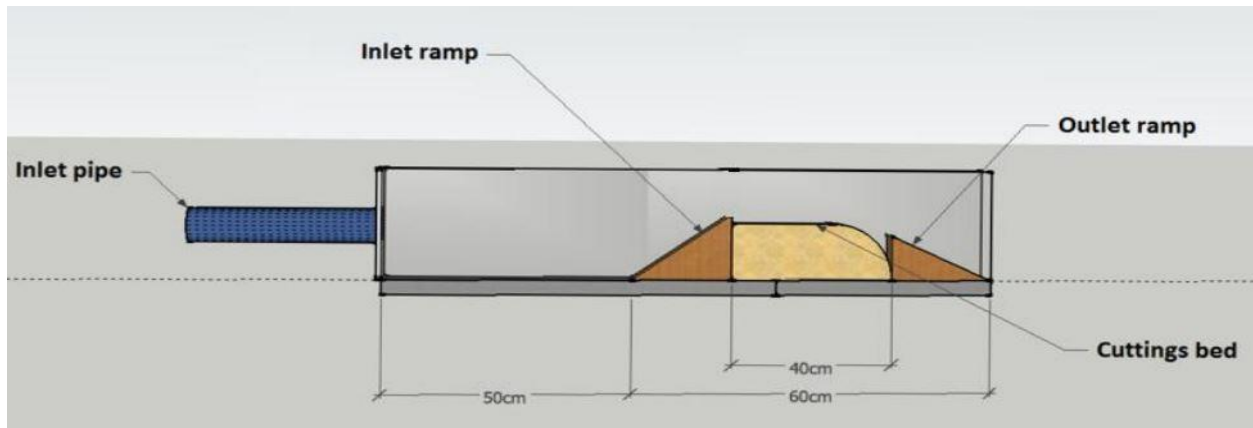


Figure 4.2: Test section of the flow loop (Isgandarzada, 2016)

4.2. Test Matrix

A total of 8 experiments was performed on the flow loop using 2 different sample of sand particles of diameter 1.5mm and 0.5mm, and 2 different fluids with varying rheology. The rheology was modified using Xanthan powder.. Each of the tests was repeated atleast four times, to ensure quality results. Table of the test matrix is shown in table 4.1.

Table 4.1: Test matrix

Variables	No. of Alteration
Sand particles	1
Flow rate (critical)	1
Rheology	2
Total	$(2*1*1)*4= 8$

4.3. Results and evaluation of model

Prior to starting the experiments, the rheological parameters for the Xanthan gum solution were measured in the NTNU mud laboratory. Viscosities of different concentration of Xanthan gum solution was measured until the desired viscosity was achieved. The viscosity was measured using the Fann viscometer model 35 SA, shown in figure 4.3.



Figure 4.3: Fann viscometer

The results of test measurement of the 0.2 % of Xanthan gum solution is shown in table 4.2. The spring factor (S) was taken to be 1. The viscosities was then calculated using the formula below

$$\mu = \theta * S * f * C \quad (22)$$

where μ - is viscosity; θ - is dial reading; S- is speed factor =1; f- spring factor= 1; C- is rotor-bob factor =1.

Table 4.2: Fann viscometer readings of 0.2 % of Xanthan gum solution

Speed RPM	Dial reading (θ)	Speed factor (S)	Viscosity (μ) lb/100 ft ²
600	18	0.5	9
300	12	1	12
200	10	1.5	15
100	7	3	21
6	3	50	150
3	2	100	200

The results of the experiments using water and Xanthan gum solution, on particles diameter of 1.5 mm are presented in Appendix C. The experiments were each repeated 4 times and critical velocities were then determined visually. To better analyze and detect the accurate critical velocities, a video recording of the experiment was done on each of the experiments, and the final results was then selected and presented in the table 4.3.

Table 4.3: Final results of the experiments

Parameters (unit)	Water	0.2% Xg solution
Fluid viscosity (Pa.s)	0.001	0.012
Critical rolling velocity (m/s)	0.23	0.12
Critical lifting velocity (m/s)	0.94	0.52

The results from the experimental works show that the rolling motion was the dominant mode of transportation of sand particles. This corresponds to the theoretical investigation done earlier in this work. At high angle inclination and horizontal wells, rolling motion is more dominant than lifting motion of the fluid on the particles. From the table above, it can be seen that the rolling and lifting critical velocities are affected by viscosity of the fluid. As can be seen from the table above, the Xanthan gum solution with higher viscosity provides better means of transportation of cuttings than water with lower viscosity. The critical rolling and lifting velocities are lower in Xanthan gum solution than it is in water.

Comparison of the theoretical and experimental results for the same particle size (1.5 mm), angle of inclination (90°) and almost same viscosities is shown in table 4.4. The fluid viscosity of water was 0.001 Pa.s for both theoretical and experimental data, while the viscosities for the plastic fluids used for the experimental and theoretical results are 0.012 Pa.s and 0.01 Pa.s respectively.

Table 4.4: Comparisons of experimental and theoretical results

Parameters	Experimental data		Theoretical data	
	Water	Plastic fluid	Water	Plastic fluid
Critical rolling velocity (m/s)	0.23	0.12	0.14	0.12
Critical lifting velocity (m/s)	0.94	0.52	0.47	0.41

The results from the table above are compared graphically in figure 4.4 and figure 4.5.

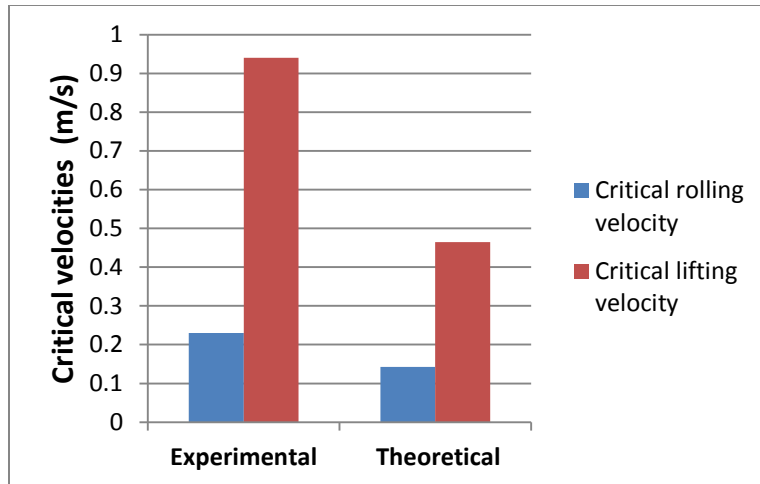


Figure 4.4: Comparisons of experimental vs. theoretical results using water

From the chart above, a big difference in the critical lifting velocities for theoretical and experimental results is noticeable. The experimental critical lifting velocity shows nearly a 50% increase from the theoretical result using water. A significant difference is also noticed in the critical rolling velocities, as the experimental result appears slightly higher than theoretical result.

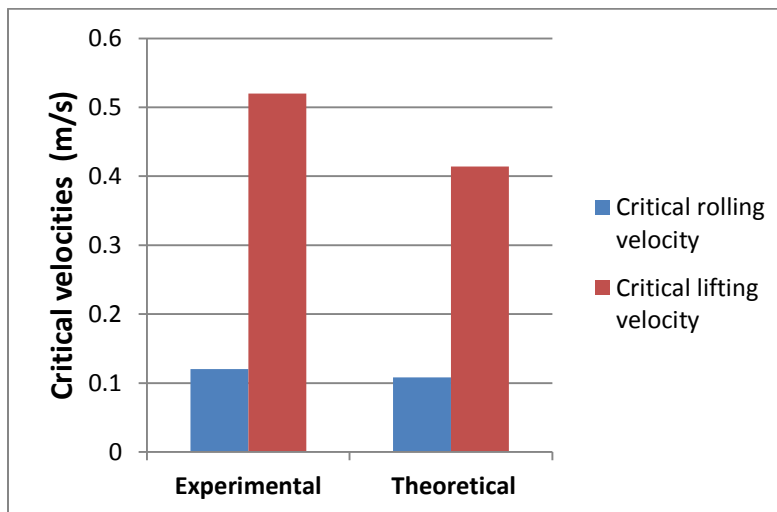


Figure 4.5: Comparisons of experimental vs. theoretical results using plastic fluids

The plastic fluids also show the same trend, as the experimental results are significantly higher than the theoretical results. Here, the experimental result of critical lifting velocity showed 26 % increase from the theoretical result.

In general, the experimental results showed the same characteristic behavior of cuttings transport as in theoretical results. Both results proved that rolling motion of particle is the dominant mode of transportation of cuttings in horizontal and highly deviated wells. The both results showed indication that lifting motion is experienced when flow rate is increased to certain value. However the model proved to be only indicative as the figures and values from both results appear to vary. The experimental results appear to be much higher than the theoretical results. The lower figures in the theoretical results could be attributed to the model not including effect of plastic and pressure forces. The plastic force effect, which is more prominent in lifting motion, was not accounted for in the model used in the theory, and as result led to lower value of the critical and lifting velocities. The experiment showed that this model can be improved by taking into account the effect of plastic forces.

5. Self-Assessment

The model used in theoretical part of this work had many assumptions. Some of the assumptions, applicable to this experiments were flawed. For instance in the case of the assumption in model that the flow is fully developed and stabilized, this may be true for low velocities, but not so for high velocities as the developing section of the flow loop, used in the experiments is not long enough to stabilize the flow for high flow rates. Also the model did not include the effect of plastic forces and pressure forces in calculating the critical rolling and lifting velocities, which could have led to low values obtained in the theoretical results. These assumptions, apparently affected the outcome of the results of critical rolling and lifting velocities.

The experimental set-up for this thesis work was not entirely suitable for the objective of the author's work. The flow loop, used for this work, was best designed for analyses of hole cleaning problems in horizontal wells. Simulating and observing transportation of cuttings in low inclination (30°) and high angle (60°) section of wellbore on this flow loop was not feasible.

Observing the critical lifting velocity of transportation of cuttings was quite challenging using this experimental set-up, as the length and design of the loop does not allow to easily and efficiently identify the lifting velocities of the sand particles.

In general, the quality of experiments was considerable good, as the experiments were each repeated atleast 4 times. And the results obtained experimentally had the same indicative results as the theoretical results.

In the absence of constraint on time and resources, further studies and analyses, deemed relevant for improved knowledge and understanding of this work includes:

- Improve the model by investigating and including the effect of plastic and pressure forces when computing the critical rolling and lifting velocities.
- Modify the experimental loop such that, the developing section will have enough length to actually stabilize the flow at high flow rates.
- Construction/modification of the flow loop to enhance qualitative analyses of cuttings transport in directional (Low and high angle) wells. The modification will give a better structure and channel to investigate and observe the critical velocities in directional and horizontal section of the flow loop.

6. Conclusion

Hole cleaning and hydraulics are important part of drilling operations that need to be carefully reviewed and incorporated in drilling program. Poor hole cleaning could lead to various problems like slow rate of penetration (ROP), excessive torque and drag, excessive wear on bit, pipe sticking problems, and possibly fracturing of formation, etc. Theoretical and experimental works on cuttings transport was carried out in this work, with emphasis on critical rolling and lifting velocities of transportation of cuttings. The following conclusion was reached from the comparisons of theoretical and experimental results:

- In highly inclined and horizontal wells, rolling motion of particle is the dominant mode of transportation of cuttings.
- Critical rolling and lifting velocities are affected by fluid viscosity, as both velocities were observed to be lower in the fluid with higher viscosity.
- Particles of larger diameter have higher critical rolling and lifting velocities compared to particles of smaller size.
- Plastic forces had effect on critical rolling and lifting velocities. The theoretical model implemented in this work did not take into account the plastic and pressure forces, thus leading to lower values of the theoretical results compared to the experimental works.

Nomenclature

Abbreviations

P-HAR	Pipe to hole ratio
PV	Plastic viscosity
ROP	Rate of penetration
RPM	Revolution per minute
YP	Yield point

Latin letters

C'	Chezy-coefficient related to grains
C_D	Drag coefficient
C_L	Lift coefficient
dp	Particle diameter
D_{hole}	Wellbore diameter
D_{pipe}	Drill pipe diameter
D_R	Drag ratio
F_D	Drag force
F_L	Lift force
K	Consistency index
n	Power law index
Re	Reynolds number
Rep	Particle Reynolds number
s	Specific density
T	Transport stage parameter
\bar{u}	mean flow velocity;

$u_{*,cr}$	Critical bed-shear velocity
u_{Lift}	Critical lift velocity
u_{roll}	Critical rolling velocity
v_c	Critical fluid velocity
V_r	Particle velocity relative to flow
w	Angular velocity of the particle
w_s	Particle fall velocity
w'	Vertical velocity component of particle
y	Vertical distance from mean bed level

Greek letters

α	Angle of inclination
ρ_p	Particle density
ρ_f	Fluid density
τ	shear stress
τ_y	Yield stress
μ	Dynamic viscosity
ν	kinematic viscosity coefficient
Φ	Angle of repose
θ_{crs}	Critical mobility parameter

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Appendix A: Summary of earlier works on hole cleaning

A summary of previous works on hole cleaning is presented in table A.1.

Table A.1: Summary of previous works on hole cleaning

Source	Key factor	Additional factor	Experimental facility	Conclusions
Li et al. (1999)	Fluid flow		BJ Services	The carrying capacity increases dramatically for flow rate larger than critical cuttings transport velocity
Okrajni et al. (1986)	Mud rheology	Flow pattern	UTDRP	In laminar flow, higher mud yield values and YP/PV provide better cuttings transport. Cuttings transport was not affected by mud rheology in turbulent flow.
Saasen et al. (1998)		Drillpipe rotation		Pipe rotation leads to more efficient cuttings transport for gel structure cuttings bed.
Li et al. (1999)		Inclination	BJ Services	Hole cleaning is more efficient with a low viscosity fluid in turbulent flow for horizontal/near horizontal wellbore, or with a high viscosity fluid in laminar flow for the vertical/near vertical wellbore.
Peden et al. (1990)	Inclination		Heriot-Watt U	Hole angles between 40° and 60° are the worst angles for transportation of cuttings for both rolling and in suspension form.
Okrajni et al. (1986)			UTDRP	Cuttings are harder to be transported at 45°-55° angle.
Brown et al. (1989)			BP Research Centre	The poorest removal rates generally occur with angles in the region of 50 to 60 degrees.
Peden et al. (1990)	Drill pipe rotation	Fluid viscosity and velocity, eccentricity, and hole size	Heriot-Watt U	Pipe rotation has a significant effect on the minimum fluid velocity in medium or highly viscous fluids. MTV was reduced in the +50% eccentricity but there were no noticeable effects of pipe rotation in -50% eccentricity. In small annuli, good hole cleaning can be obtained.
Sifferman et al. (1992)		Inclination, particle size, ROP	Southwest Research	Pipe rotation has the greatest effect on hole cleaning at inclination near horizontal, for small cuttings, and low ROP.

Source	Key factor	Additional factor	Experimental facility	Conclusions
Sanchez et al. (1999)	Pipe rotation	Motion manner, flow rate and inclination	UTDRP	Orbital motion can efficiently improve hole cleaning. At 90 degrees and low flow rates high rotary speed produce the most benefits. Higher rotary speeds are better in lower inclinations.
Saasen et al. (1998)	Pressure drop			Cuttings bed height is reduced when the frictional pressure drop is increased.
Li et al. (1999)	ROP		BJ Services	Increasing ROP results in the higher bed height for fixed liquid flow rate. For a given ROP, higher fluid flow rate results in a lower and bed height.
Wang et al. (1995)	Mud density		University of Petroleum	Cuttings bed height and critical cuttings transport velocity decrease with the increase in mud density.
Bassal (1995)	Particle size	Size from 2 to 7 mm	UTDRP	Smaller cuttings are slightly harder to clean out.
Martins et al. (1996)		Size from 2 to 6 mm	Petrobras	Larger particles are always harder to be transported than smaller ones
Sanchez et al (1999)		Size from 2 to 7 mm	UTDRP	At high rotary speed and with high viscosity mud, the smaller cuttings are easier to transport.
Peden et al. (1990)		Size from 1.7 to 3.35 mm	Heriot-Watt U	Smaller cuttings were more difficult to transport at all angles of deviation with low viscosity fluid. While larger cuttings were easier to transport at low angles (from 0° to 50°) with high viscosity fluid.
Okrajni et al (1986)	Pipe eccentricity	Inclination	BJ Services	Solids transport is affected slightly by eccentricity at low angles, but as the inclination angle is increased the effect becomes significant in laminar flow.
Wang et al (1995)			University of Petroleum	Cuttings concentration increases as the eccentricity is increased. Pipe eccentricity makes critical annular velocity increase.

Appendix B: Slip velocity

The theories and derivation of slips velocity for both perfect and imperfect spheres is presented in this appendix.

Slip velocity of perfect sphere

Rate of cutting generation can be calculated as follow (Skalle, 2015):

$$q_{cuttings} = \frac{\pi}{4} d_{bit}^2 Rop \quad (B.1)$$

At the same time, initial cuttings concentration at bottom of annulus while drilling becomes

$$C_{cuttings,0} = q_{cuttings}/(q_{pump} + q_{cuttings} - q_{filling}) \cong q_{cuttings}/q_{pump}$$

The rate of “falling” or settling of cuttings at bottom of hole can be calculated starting with equating the two forces (gravity and stress) acting on particles in stationery, laminar flow.

$$(\rho_p - \rho_{mud})V_{sphere} = \tau A_{sphere} \quad (B.2)$$

where

$$\tau = \mu \frac{dv_x}{dr},$$

$$V_{sphere} = \frac{4}{3}\pi r^3 = \frac{\pi}{6}d_p^3$$

$$A_{sphere} = 4\pi r^2 = \pi d_p^2$$

Slip velocity can be deducted using Stokes law of falling sphere expressed as follow

$$V_{slip} = \frac{d_p^2 g (\rho_p - \rho_{mud})}{6\pi\mu} \quad (B.3)$$

The above expression is only valid for small sized spherical particle ($r < 0.1$ mm) , and laminar flow around the particle, $N_{Re,p} \leq 1$ which can be calculated as:

$$N_{Re,p} = V_{slip} d_p \rho_{mud} / \mu_{eff} \quad (B.4)$$

Slip velocity of imperfect spheres

As most cuttings are non-spherical, and flow regime can vary ultimately in well profile, empirical knowledge is of paramount importance.

Sphericity of cutting particle is the ratio of the surface area of sphere of same volume to the surface area of the particle.

$$\text{Sphericity} = \frac{A_s(\text{sphere})}{A_s(\text{Particle})} \quad (B.5)$$

The table below shows the sphericity of cutting particles of different shapes.

Table B.1: Sphericity of cuttings particles

shape	sphericity
Sphere	1.0
Octahedron	0.85
Cube	0.81
Prism	0.77

For imperfect sphere, the two forces acting on slipping cuttings are gravity and drag force. The slip velocity can be found using the formula from drag force and drag coefficient given as

$$F_{Drag} = C_{Drag} 0.5 A_p \rho_{mud} V_{slip}^2 = C_{Drag} d_s \frac{\pi}{8} V_{slip}^2 \quad (B.6)$$

The slip velocity is then found through the expression below

$$V_{slip} = \sqrt{4 g(\rho_p - \rho_{mud})d_p / (3C_{drag} \rho_{mud})} \quad (B.7)$$

The figure below shows the relationship of C_{Drag} and Reynolds' number for different flow regime

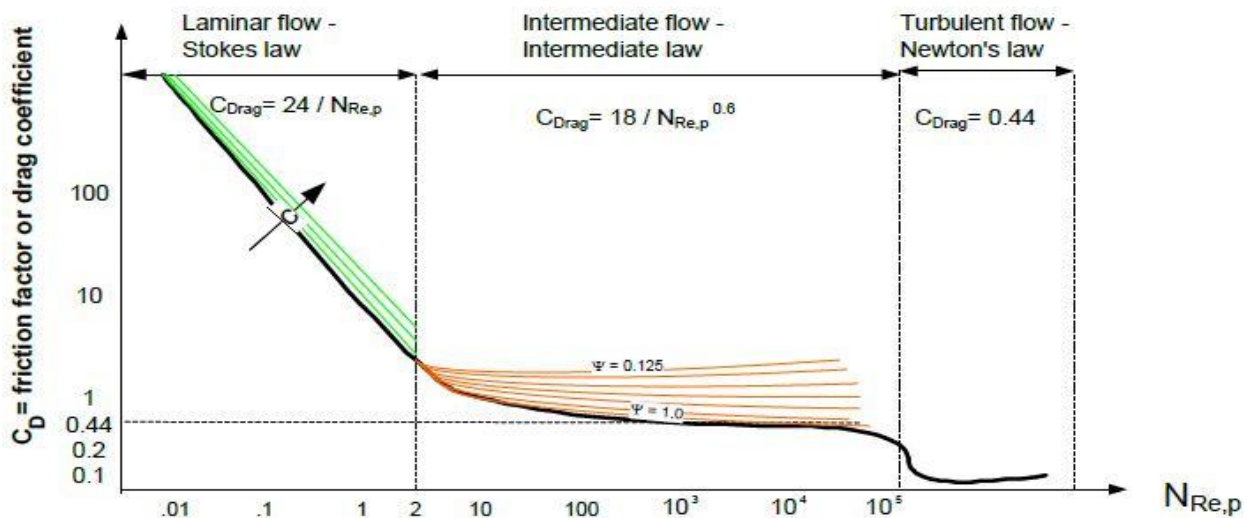


Figure B.1: Relationship between Drag coefficient and Reynolds number for settling particles in Newtonian fluids

Appendix C: Results of experiments

The results of the calibrated flow velocities and observed motion are shown in table C1.

Table C.1: Particle motion type of calibrated velocities

Particle size, mm	Fluid viscosity (Pa.s)	Critical velocity, m/s	Reynolds number		Observed motion type
1.5	0.001	0.10	150	16.6	Rolling
1.5	0.001	0.12	180	20	Rolling
1.5	0.001	0.23	345	38.33	Rolling
1.5	0.001	0.35	525	58.33	Rolling
1.5	0.001	0.52	780	86.67	Rolling &Lifting
1.5	0.001	0.94	1410	153.3	Rolling &Lifting
1.5	0.001	1.26	1890	210	Rolling &Lifting
1.5	0.001	1.57	2355	263.3	Bed-load motion
1.5	0.001	2.10	3150	350	Bed-load motion

The results of repeated experiments for finding critical rolling and lifted velocities are presented in table C2.

Table C.2: Results of experimental works on flow loop

Critical velocities (m/s)	Water	0.2 % Xanthan gum solution	
u_{roll}	0.23	0.12	16.6
u_{roll}	0.23	0.12	20
u_{roll}	0.23	0.23	38.33
u_{roll}	0.23	0.12	58.33
u_{lift}	0.94	0.35	86.67
u_{lift}	0.52	0.52	153.3
u_{lift}	0.94	0.35	210
u_{lift}	0.94	0.35	263.3