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UNIVERSITI TEKNOLOGI PETRONAS

INVESTIGATION ON THE CUTTING PARTICLES TRANSPORT IN HORIZONTAL WELL DRILLING

By

RAWIA ABD ELGADIR ELTAHIR ELTILIB

The undersigned certify that they have read, and recommend to the Postgraduate Studies Programme for acceptance this thesis for the fulfillment of the requirements for the degree stated.

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INVESTIGATION ON THE CUTTING PARTICLES TRANSPORT IN

HORIZONTAL WELL DRILLING

By

RAWIA ABD ELGADIR ELTAHIR ELTILIB

A Thesis

Submitted to the Postgraduate Studies Programme
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**Dedication**

*To my family*

*To my friends*

*To my colleagues*

*To special persons in my life*

# Abstract

Arguably the most important prerequisite function to permit further progress in well drilling operations up to reach production is a complete removal of drilled cuttings from the well bore. This target becomes more challenging in highly-deviated to horizontal wells, where the cuttings particles have more tendency to accumulate in the lower side of the well bore and form a bed of standstill cuttings. In this study, a mathematical model based on the mechanistic theory and the three-layer approach was developed to simulate the cutting particles transport in annular flow during the horizontal drilling process. Two mathematical models were developed to investigate the cuttings transportation performance in horizontal wells. Due to high non- linearity, both were solved numerically after conversion to computer algorithms using MATLAB. The master model examined the performance of irregular shaped cuttings transported in concentric annulus by non-Newtonian fluids. The model predicted the velocities of the layers, the layer's concentration, the dispersive shear stress, and the pressure drop. The transport performance was adequately simulated under various operational and design conditions, namely the effect of the cuttings size, cuttings shape, annular size, rate of penetration and the mud rheology in term of fluid viscosity. The second model represented a modified model which used to test the sensitivity of the frictional forces calculations, where empirical correlations were employed to replace Szilas formula to calculate the layers and wall friction stresses. The cuttings size, mud viscosity and annular size demonstrated significant effect on transport process. While the operational rate of penetration performed the lowest effect between the entire parameters of the cuttings transport. The results compared favorably with those obtained by previous investigators. Accordingly, the simulations demonstrated that the basic model could be used to analyze the cuttings transport. Thereby, it could potentially be used as design and/or analysis tools for the follow-up of transport processes in horizontal wells.

## Abstrak

Lazimnya, kepentingan fungsi prasyarat adalah untuk menyingkirkan keseluruhan serpihan-serpihan gerudi dari lubang telaga bagi menperolehi pencapaian yang bagus dalam operasi penggerudian telaga hingga ke peringkat pengeluaran. Target ini menjadi lebih mencabar bagi telaga yang sangat berarah dan telaga mendatar, di mana zarah-zarah serpihan gerudi mempunyai kecenderungan untuk berkumpul di bahagian dasar lubang telaga dan membentuk satu mendakan serpihan-serpihan yang tidak bergerak. Dalam kajian ini, model matematik berdasarkan teori mekanistik dan pendekatan tiga lapis telah dikembangkan untuk mensimulasikan pengangkutan zarah-zarah serpihan dalam aliran annular semasa proses penggerudian mendatar. Dua model matematik telah dihasilkan untuk menyiasat prestasi pengangkutan serpihan-serpihan. Oleh sebab kualiti bukan linear yang tinggi, kedua-duanya dipecahkan secara berangka selepas penukaran ke komputer algoritma menggunakan MATLAB. Model master menyemak prestasi serpihan-serpihan yang berbentuk tidak teratur diangkut dalam annulus konsentrik oleh bendalir bukan Newtonian. Model telah meramalkan kelajuan lapisan, kepekatan lapisan, tegangan geseran dispersif, dan penurunan tekanan. Prestasi pengangkutan telah disimulasikan dengan pelbagai keadaan operasi dan rekabentuk, iaitu kesan saiz serpihan, bentuk serpihan, saiz annular, kadar penetrasi, dan rheologi lumpur. Model kedua merupakan model yang telah diubahsuai untuk digunakan dalam menguji sensitiviti pengiraan daya geseran, di mana, korelasi empirik telah digunakan untuk menggantikan Szilas formula bagi mengira lapisan dan ketegangan geseran dinding. Saiz serpihan, rheologi lumpur dan saiz annular menunjukkan pengaruh yang besar kepada proses pengangkutan. Sedangkan kadar penetrasi adalah parameter yang lebih rendah kesannya dalam pengangkutan serpihan-serpihan gerudi. Hasil daripada kajian ini telah dibandingkan dengan hasil kajian yang diperolehi oleh penyelidik-penyelidik sebelum ini. Simulasi telah menunjukkan bahawa kedua-dua model boleh digunakan

untuk menganalisis pengangkutan serpihan-serpihan gerudi. Dengan demikian, ia berpotensi untuk digunakan sebagai rekabentuk dan/atau alat analisis untuk tindakan lanjut proses pengangkutan di telaga mendatar.

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## Nomenclature

| Symbol | Nomenclature | Unit |
|---|---|---|
| $A_a$ | Cross section area of the annulus | $in^2$ |
| $A_b$ | Cross section area of the stationary-bed layer | $in^2$ |
| $A_m$ | Cross section area of the moving-bed layer | $in^2$ |
| $A_s$ | Cross section area of the suspended layer | $in^2$ |
| $A_x$ | Cross section area of the a layer | $in^2$ |
| $c_b$ | Mean volumetric concentration of cuttings in stationary-bed layer | - |
| $c_m$ | Mean volumetric concentration of cuttings in moving-bed layer | - |
| $c_s$ | Mean volumetric concentration of cuttings in suspension layer | - |
| $c_{sl}$ | Local cuttings concentration in suspended layer | - |
| $c_t$ | Total volumetric concentration cuttings in annulus | - |
| $c_x$ | Total volumetric concentration cuttings a layer | - |
| $D_h$ | Hydraulic diameter of layer | in |
| $D_p$ | Drill-pipe diameter | in |
| $d_p$ | Mean diameter of drilled cutting | in |

| | | |
|---|---|---|
| $dp/dz$ | Pressure drop | Psi/ft |
| $D_w$ | Well diameter | in |
| $dz$ | Well length | ft |
| $f_b$ | Friction factor between the channel and bed layer | - |
| $F_B$ | Buoyancy force | $lb_f$ |
| $F_b$ | Force between stationary-bed layer and walls | $lb_f$ |
| $F_d$ | Dry force at well boundary and moving-bed layer | $lb_f$ |
| $F_D$ | Drag force | $lb_f$ |
| $F_g$ | Gravity force | $lb_f$ |
| $F_L$ | Lift force | $lb_f$ |
| $F_m$ | Force between moving-bed layer and walls | $lb_f$ |
| $f_m$ | Friction factor between the channel and moving-bed layer | - |
| $F_{mb}$ | Friction force between moving-bed and stationary-bed layers | $lb_f$ |
| $f_{mb}$ | Interfacial friction factor between the moving and stationary bed layer | - |
| $F_n$ | Normal force | $lb_f$ |
| $f_p$ | Friction factor between the channel and drill-pipe | - |
| $F_s$ | Force between suspension and walls | $lb_f$ |
| $f_s$ | Friction factor between the channel and suspension layer | - |

| | | |
|---|---|---|
| $F_{sm}$ | Friction force between suspension and moving-bed layers | $lb_f$ |
| $f_{sm}$ | Interfacial friction factor between the suspended and moving bed layer | - |
| $F_{\Delta P}$ | Pressure force | $lb_f$ |
| $g$ | Gravity | $ft/s^2$ |
| $h_b$ | Thickness of the stationary-bed layer | in |
| $h_s$ | Thickness of the suspension | in |
| $K$ | Fluid consistency | $lb_f.s^n/ft^2$ |
| $k$ | Von Karman constant = 0.4 | - |
| $K_s$ | Consistency index of fluid in suspension | $lb_f.s^n/ft^2$ |
| $n$ | Fluid flow behavior index | - |
| $Re_{gen}$ | Generalized Reynolds number | - |
| $Re_m$ | Reynolds number of moving-bed | - |
| $Re_p$ | Cutting particle Reynolds number | - |
| $Re_s$ | Reynolds number of suspension | - |
| $S_b$ | Perimeter of stationary-bed contact with the well | in |
| $S_m$ | Perimeter of moving-bed contact with the well | in |
| $S_{mb}$ | Perimeter surface between the moving-bed and stationary-bed layer | in |
| $S_p$ | Perimeter of the drill-pipe | in |

| | | |
|---|---|---|
| $\boldsymbol{S_s}$ | Perimeter of suspended layer in contact with the well | in |
| $\boldsymbol{S_{sm}}$ | Perimeter surface between the suspended and moving-bed layer | in |
| $\boldsymbol{t_m}$ | Thickness of the moving-bed layer | in |
| $\boldsymbol{TT}$ | Total bed layers height (stationary + moving-bed) | in |
| $\boldsymbol{U_a}$ | Mean annular fluid velocity | ft/s |
| $\boldsymbol{U_b}$ | Mean velocity of the stationary-bed layer | ft/s |
| $\boldsymbol{U_m}$ | Mean velocity of the moving-bed layer | ft/s |
| $\boldsymbol{U_s}$ | Mean velocity of the suspended layer | ft/s |
| $\boldsymbol{U_x}$ | Mean velocity of a layer | ft/s |
| $\boldsymbol{U_\tau}$ | Frictional velocity | - |
| $\boldsymbol{v_h}$ | Hindered settling velocity of cutting particles | cm/s |

## Greek Symbols

| **Symbol** | Nomenclature | Unit |
|---|---|---|
| $\boldsymbol{\mu_{dyn}}$ | Dynamic friction coefficient | - |
| $\boldsymbol{\mu_e}$ | Effective fluid viscosity | $lb_f.s/in^2$ |
| $\boldsymbol{\mu_{st}}$ | Dynamic friction coefficient | - |
| $\boldsymbol{\beta}$ | Inclination angle | Degree |
| $\boldsymbol{\Gamma}$ | Diffusivity | $in^2/s$ |
| $\boldsymbol{\theta_b}$ | Angular thickness of the stationary-bed layer | Degree |
| $\boldsymbol{\theta_m}$ | Angular thickness of the moving-bed layer | Degree |
| $\boldsymbol{\rho_b}$ | Effective density of the stationary-bed layer | $lb_m/in^3$ |
| $\boldsymbol{\rho_f}$ | Fluid density | $lb_m/in^3$ |
| $\boldsymbol{\rho_m}$ | Effective density of the moving-bed layer | $lb_m/in^3$ |
| $\boldsymbol{\rho_p}$ | Particle density | $lb_m/in^3$ |
| $\boldsymbol{\rho_s}$ | Effective density of the suspended layer | $lb_m/in^3$ |
| $\boldsymbol{\rho_x}$ | Effective density of a layer | $lb_m/in^3$ |
| $\boldsymbol{\tau_b}$ | Interstitial fluid shear stress between the stationary-bed and well wall | $lb_f/in^2$ |

| | | |
|---|---|---|
| $\tau_{dis}$ | Equivalent dispersive shear stress between the stationary and moving-bed layers | $lb_f/in^2$ |
| $\tau_m$ | Fluid shear stress between the well wall and suspended layer | $lb_f/in^2$ |
| $\tau_{mb}$ | Fluid shear stress between the stationary and moving bed layer | $lb_f/in^2$ |
| $\tau_s$ | Interstitial shear stress between the annular and suspended layer | $lb_f/in^2$ |
| $\tau_{sm}$ | Interfacial shear stress between the suspended and moving-bed layer | $lb_f/in^2$ |
| $\varphi$ | Particle sphericity | - |
| $\varphi_D$ | The equivalent dynamic friction angle = 0.75 | - |

# Chapter 1

# Introduction

## 1.1 Background

In well drilling, cuttings transport is the mechanism by which pieces or rock debris created by the bit tool motion is removed through the annular space between the well and drill pipe/string/coiled tubing surface using proper carrier fluid, i.e. drill-mud. Cuttings removal occurs by means of two-phase flow. The drill-mud flows to the down-hole through the drill-pipe or drill string, fills the annulus, carry the drilled cuttings and remove them out of the well-bore [5]. During removal, drilled cuttings flow in opposite direction to the bit penetration, as shown in Figure 1-1 [6][1]. The transport process is also known as hole cleaning operation, in which the waste cuttings will be separated and handled by another means to save the environment.

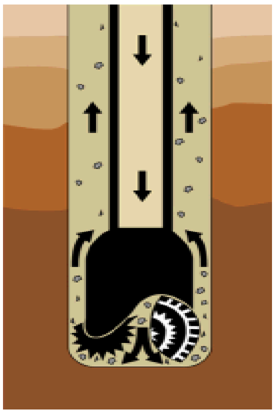

Figure 1-1: Process of well drilling and hole cleaning [6]

[1] Image from [1], accessibility before Tuesday, 9 Feb, 2010 9: 16 AM

Since the first oil well was drilled in Titusville 1859 [7], up to present times, several problems have emerged and maintained a special prominence in the field of well drilling. Simultaneously, several benefits were gained from wells and needs are hugely increased as well. In order to cope with these needs of globalization, oil and gas fields are developing more sophisticated drilling methods, production schemes and technology. The Trajectories of wells are now extended to be established in inclined and horizontal drilling as shown in Figure 1-2, with high extended reach, multi-branches and ultra deep offshore wells.

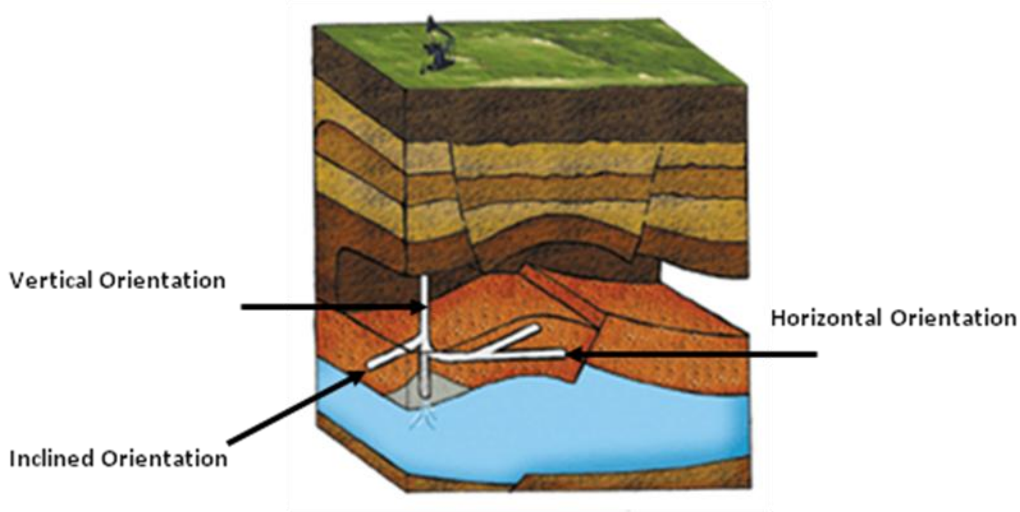


Figure 1-2: Vertical and directional wells drilling [1]

## 1.2 Problem Statement

Currently, there is no general method of drilling operation application that can assure the operator of optimal drilling performance, independent of conditions, equipment and objectives. Thus, intention of the drilling technology is to enhance an effective drilling technique, in order to reduce both cost and time of the operation and improve recovery from reservoirs.

Even with such knowledge of cuttings behavior, there are some limitations concerning control of the annular environment [8]. The problem for this present research can be explicitly placed within three major aspects as following:

### 1.2.1 The Two-phase Flow Problem

The transport of cuttings occurred during the drilling operation is an engineering application which involves solid-liquid two-phase flow. The liquid-phase is mostly a non-Newtonian fluid known as drill-mud which formulated as either water or oil based system [9].

### 1.2.2 Non-vertical Drilling Orientation Problem

By non-vertical or directional borehole practices, drilling operation can be performed in various kinds of reservoirs by implementing inclined and horizontal drilling orientations and this is more advanced and complicated than the traditional vertical wells. Recently, horizontal well applications have been practiced in many plants around the world. The major purpose of horizontal drilling is to enhance reservoir contact over vertical drilling, and thereby enhance the productivity of the well. Besides, the main objective of the horizontal drilling is to intersect multiple zones. [10].

### 1.2.3 Non-Newtonian Fluids Problem

Non-Newtonian fluids are kind of fluids those perform a complicated behavior during their flow. However, for necessity drill-muds are optimized to possess behavior of the non-Newtonian fluids to accomplish their functions [9].

Due to lack of recommendation in the field, a series of problems were recognized in wells drilling, i.e. (losing of a 3000 ft, $60^o$ inclined well in Texas Gulf Coast) [11]. These problems increased the disaster expectations in the field of the wells drilling. Malfunction of drilling tools, drilling preparation and re-drilling incurs costs of millions of dollars. Several costs start with exploration, development of the oil field, rig, drilling tools and equipment up to the final production steps. Hence, the drilling operation cost has significant importance in the total cost. However, compared to the tragic consequences of losing the well itself those are very low costs. Therefore, such an annoying problem should be handled with more consciousness, wisdom and knowledge, in order to develop an efficient drilling and transport technology that preserves the well intact. Hence, maintaining of a successful drilling operation is a great challenge which basically depends upon the removal of all drilled cuttings out of the wellbore.

It can be concluded that the combination of the three major sources of complications represent a serious challenge to modeling and analyzing the process of cutting transport in inclined and horizontal oriented wells.

In the directional cuttings transport, aggregation of settled particles due to the low cutting fluidity and high static fraction returned high stationary bed or slow motion [12]. Cutting particles tends to settle downward responding to the gravity force while contrasted forces acting on the cuttings struggling to overcome settling. As result, further accumulation of particles in the conduit would reduce the flow area. In the oil well drilling application, this will generate many problems, such as low ROP ,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 [9][4].Those problems could finally lead to terminate of the drilling operation and loose the well itself.

### 1.3 Objective of the Study

In view of the problem statement, the most critical and interesting problem in drilling operation has been the efficient removal of the cuttings. Therefore, the main purpose of this study is to develop a three-layer, mathematical model in order to simulate the drilled cuttings transportation, to estimate the performance of the horizontal wells cleaning, with more focus on the effect of the cutting particles and other drilling parameters.

In general, this study aimed to:

- To investigate settling and hindered behaviors of particles and to determine the two-phase annular flow of cuttings-mud during the cleaning process of horizontal well drilling.
- To estimate the transport performance under different operating (annular velocity and arte of penetration)
- To estimate the transport performance under various design conditions (annular size and mud viscosity).

**1.4 Scope of the Study**

The solution of the three inter-related problems of solid-liquid and non-Newtonian fluid flow and flow through horizontal annulus presented a formidable challenge. Because of the competitive advantages of modeling over experiments such as availability, flexibility in addition to the time and cost factors, this research initiative was intended to undertake a mathematical modeling technique specifically adopting the three-layer approach based on a mechanistic model to perform a study of cuttings transport through the horizontal annulus.

The study covered a variety of operational cases in which the effect of mud discharge was examined over the turbulent annular flow. Moreover, operational and design parameters were also involved in this study, through investigation of the operational Rate of Penetrations or, (ROP) and the annular size.

In this context, the effect of the rheological property in term of mud viscosity was investigated by changing of the power law viscosity ($n$ and $K$).

The cutting particles specifications were accounted for, by adopting various types of particle sphericities and sizes.

The scope of the study involved:

A. Obtain the requirements of the drilled cutting particles movement in the cleaning operation.

B. Model the two-phase annular flow of cuttings-mud during the transport in horizontal wells drilling.

C. Implement a new method of layers model for annular flow and transport of non-sphere particles derived from the bases of non-Newtonian channel flow and sphere particles transport.

D. Code the two-phase model into a computer program using MATLAB soft ware to simulate the horizontal transport of drilled cuttings.

E. Conduct a parametric study for some factors affecting on the transport and examine the model performance by compare with previous studies.

### 1.5 Summary and Layout of the Thesis

This dissertation is subdivided into seven separate chapters. The introduction chapter presents introductory remarks about the drill cuttings transport process and its cohesive importance in the well drilling operations. Then, in the statement of problem section, problems associated with the cuttings transport and the procedures to solve this problem and provide further understanding in the topic of drilling operation is given. Furthermore, the objectives of the work, the scope of the study and the main features of the methodology have also been provided in the introductory chapter.

Presentation, critical evaluation and discussion of other related research on cuttings transport are reported in the second chapter (the literature review). Special consideration is directed to the modelling techniques used, and to the three-layer approach studies. Comments and some conclusion were provided at the end of the second chapter.

Likewise, the third chapter generalizes the overall strategy and methodology of the research. This chapter demonstrates the details of the two mathematical models which were built to simulate the horizontal cuttings transport. Models hypotheses and importance of some essential equations was highlighted in chapter four. Furthermore this chapter underlines the solution procedures that followed to code and solve the mathematical model using MATLAB.

Chapter four documents preliminary results which displays the behaviours of particles settling and hindered settling. Moreover the chapter presents the obtained simulation results for the different parameters studied. Additional results are also presented in this chapter to provide a comprehensive comparison for the basic model results trend and to validate the usability of the model. A concise outcome was arrived at after rigorous analyses which facilitated evaluation of the developed model performance.

The last chapter provides a conclusion for the preceding chapters. Major outcomes from the work is summarised in this chapter. For further improving on the cuttings transport simulation, valuable recommendations are highlighted on the basis of the generated model results and subsequent conclusions pointed out.

A list of figures, tables and acronyms used in the model formulations are provided at the beginning of the thesis. A list of all references used to develop this research and necessary appendices are also attached at the end of this dissertation

# Chapter 2

# Literature Review

## 2.1 Introduction

Transportation of cutting particles is known as a mechanism by which vital factors of drilling should effectively be employed [7]. In the solid-liquid two-phase flow during the transport process the drill-mud is utilized as a carrier for the solid-phase of rocks that are drilled by the tool-bit.

A substance is termed non-Newtonian when its flow curve is nonlinear. Alternatively, its flow curve may be linear, but it does not pass through the origin. This happens when its viscosity is not constant at a given temperature and pressure and it exhibits non-equal normal stress in a simple shearing flow. The value of the viscosity depends upon the flow conditions, such as flow geometry, shear rate or stress developed within the fluid, time of shearing, kinematic history of the sample. Under appropriate conditions, some materials can exhibit a blend of solid and fluid-like responses. Though somewhat arbitrarily, it is customary to classify the non-Newtonian fluid behavior into three general categories [13] as follows:

1. Purely viscous, time-independent, or GNF (Generalized Newtonian Fluids), where the applied rate of shear is dependent only on the current value of the shear stress or vice versa.

2. Time-dependent systems in which the relation between the shear stress and the shear rate depend upon the duration of shearing with respect to the previous kinematic history.

3. Visco-elastic fluids. Those exhibiting combined characteristics of both an elastic solid and a viscous fluid, and showing partial elastic and recoil recovery after deformation.

Drilling mud is non-Newtonian fluid that exhibits Thixotropy behavior, in which it displays a decrease in viscosity over time at a constant shear rate [14]. Most of the drilling fluids are non Newtonian fluids, with viscosity decreasing as shear rate increases [15]. This is similar behavior to the Pseudoplastic or shear thinning fluids.

At both adiabatic and non-adiabatic conditions, a two-phase flow system can be a very complex physical process. This is because such systems combine the characteristics of deformable interface, conduit geometry, flow direction, and, in some cases, the compressibility of one of the phases. In addition to inertia, viscous and pressure forces, the two-phase flow systems are also affected by the interfacial tension forces, as well as the characteristics of the phases, the exchange of mass, momentum, and energy between the phases [16]. The ability of drill-fluids to suspend and transport the drilled solids out of the wellbore is the critical target to gain a successful well drilling operation. For further expansion to the production and refinery stages, proper transport and thereby successful drilling demand an adequate drilling plan. The problem of well-bores cleaning has been recognized as a serious problem in drilling fields as long as wells have been drilled. Therefore it is necessary to identify where the critical spots are with regard to the wellbore cleaning.

Many parameters are found to affect hole cleaning operation. These may generally be categorized into major three groups as follows:

- The first group: parameters which are related to the carrier fluid, such as fluid density, fluid viscosity and fluid flow rate.

- The second group: solid cutting parameters include cuttings density, cutting shape and size and cutting concentration.

- The third group: operational parameters which may be related to geometric features or other effects. This group contains inclination, pipe rotation and pipe positioning in the hole (concentric / eccentric).

Over the previous three decades, many researchers have attempted to clarify some of ambiguities related to the matter of transport. Various studies were conducted to investigate and hopefully improve the mechanism of drilled cuttings transport. Much difficult and painstaking work was directed at trying to obtain a realistic understanding of the phenomena. It was noticed that most of the previous studies were focused upon only a few parameters while neglecting various others. This approach is a common strategy, frequently used to reduce the level of complexity of the problem. Notice that, simplifying of such problem should be done via rational assumptions to avoid distortion. An extensive survey was carried out on the available sources, such as research centers, universities, journals and conference proceedings, in addition to some private communications. Research efforts can be classified into three categories: (a) experimental investigation, (b) mathematical modeling, and (c) computational fluid dynamics or, (CFD) simulations.

Researchers working within the previously- mentioned three groups of parameters to investigate their influence and their interaction through diverse conditions of drilling practices. These efforts facilitate drilling operations and help overcome barriers involved in the directional drilling. Nearly all Former studies were excessively focused upon the transport problems in vertical wellbores. Unfortunately, there still is an absence of some the basic data required to fully evaluate the present field practices in the directional drilling operation.

The collected reviews were subdivided into three subsections. The first part reviews the experimental works. The second part reviews the mathematical and mechanistic modeling, and the third part reviewed the studies on CFD simulation. At the end of the chapter, the private communications, conclusions and comments are presented.

## 2.2 Experimental Work

Obviously, experiments were the first method of choice to investigate the transport phenomena. Normally, experimental loops oblige researchers to follow the actual field conditions in order to attain useful and reliable results. However, short laboratory loops for experiments may not yield confident and reliable results; this is because of lack of the relatively short well lengths to give the necessary settling time [17]. Different outcomes can be achieved from experimental findings, such as correlations and "rules of thumb". Those, to somehow help to simplify the complex parameters involved in the cuttings transport process. In addition, data collected from one site location is impractical to analyze the different applications of cutting transport [18].

For instance, earlier experimental studies were focused on the transport in the pipe flow and vertical well drilling. Besides, the continuous rise in the global demand for energy has lead to a continuing search for more sources of energy. These requirements of this search, together with other technical reasons, have imposed the need to introduce and implement the directional or non-vertical drilling systems. Because of this, ongoing research has become essential to enhance the knowledge needed to meet the requirement of the new methods, and also to handle any new obstacles that emerge, such as particles settling, bed formation and bed sliding.

Tomren et al. [19] performed a comprehensive experimental study in inclined wells at steady state cuttings transport. They used a 40 ft long test section with pipe rotation and eccentricity. Dividing the test into three inclination parts, they investigated numerous parameters. Their results showed that the bed thickness increases as fluid flow rate decreases, and that the fluid flow velocity plays a major role in cuttings transport. High viscous mud provided better transport than low mud viscosity. These same authors confirmed that use of the transport ratio (average particle velocity to annular velocity) to evaluate the performance of the inclined transport was misleading. Hence, use of this ratio should be restricted on the vertical transport due to the existence of solids segregation. They also visually identified the occurrence of sliding beds in some critical angles. These findings support the hypothesis of layers occurrence during the annular directional transport.

Okranjni and Azar [20], experimentally studied the effects of mud rheology on cuttings transport in directional wells. They studied some of mud properties, such as apparent viscosity, plastic viscosity, yield value and gel strength. They identified three zones of inclination, and suggested that laminar flow dominated transport at the lower range zone (0-45$^{o}$). At high angle zones (55-90$^{o}$), turbulent flow was required to achieve cuttings removal. However, at the intermediate inclination (45-55$^{o}$), both laminar and turbulent, flow demonstrated the same effect. Since different mud could have the same rheological properties, they found that higher Yield Point or (YP) -where the permanent deformation of a stressed specimen begins to take place- and ratio of yield point to the Plastic Viscosity or (PV) -which is the slope of the shear stress/shear rate line above the yield point- provides good transport, and that these parameters have more significance at the lower flow velocities. In the turbulent flow, mud rheology does not affect the transport. The researchers suggested that cuttings volumetric concentration is a very important parameter. Thus, the worst cutting transport was pronounced at high concentration, which takes place at inclination combined with relatively low flow rates. They also claimed that the flow rate of mud is a dominant parameter in hole cleaning.

A complementary experimental and theoretical study was carried out by Brown et al. [21]. Their investigations focused on deviated holes cleaning. A 50 ft long loop was designed to simulate the field conditions under various modes with an eccentric rotated drill-pipe. The complimented mathematical model was programmed. The results showed that water in a turbulent flow was most efficient in transport. At low annular velocities, viscous fluids were inevitably used to transport cuttings for low holes deviations.

After series of problems, and due to the loss of a 3000 ft, 60$^{o}$ inclined well in Texas Gulf Coast, Seeberger et al. [11] carried out an emergent experimental study in order to solve cuttings removal problems in highly deviated wells. Informed by a detailed review of the lost well's problem, researchers set up their flow loop to study large diameter deviated wells using field oil/water-based mud. They found that oil-based mud has a lower efficiency than water-based mud for cuttings removing, and oil-based mud needs additives in order to meet the qualifications for cuttings removal. They also reported that oil-base mud and water-based polymer fluids could be equally efficient for the transport of cuttings once they possessed the similar rheological properties.

Ford et al. [22]investigated drilled cuttings transport in inclined boreholes experimentally. Their study aimed to determine the effect of the drilling parameters on the needed circulation rate in order to ensure efficient transport. Using 21 ft allow (0-90$^{o}$) angles of inclination with rotating tubes; they identified two transport mechanisms to clean the holes. The first mechanism was the rolling/sliding motion, and the second was suspension by the circulating fluid. In addition seven flow patterns were observed. Accordingly, they defined the Minimum Transport Velocity or, (MTV) as the point at which cuttings are being visually transported up the annulus. Therefore, MTV can be used to measure the drilling fluid carrying capacity. They concluded that the fluid annular velocity is sensitive to the degree of deviation angle, and the required annular velocity for transportation is a function of the cuttings size. With Newtonian fluids (water), rotation was found to have a minor effect on the transport of cuttings. Cutting transport depends not only upon the rheology of fluids, but also depends upon whether the flow is laminar or turbulent. Furthermore, they also recorded that the MTV required for transport by each of the two mechanisms increases with the particle size, and vice versa.

Sifferman and Becker [23] presented several multifactor experiments which covered a wide range of variables affecting cuttings particle accumulation and bed formation. The ten parameters involved in this study have distributed and emerged into three phases in order to achieve the interrelation between the variables, and to adjust of the controllable factors. A 60 ft long 3 x 4.5 inch annular section that provided various hole deviation angles (45-90$^{o}$) was used in this study. The results of statistical analysis showed that the most influential variables in the bed were the annular velocity, the mud density, the inclination angle and the drill pipe rotation. Also, they reported that the cleaning efficiency partially depends upon the particle size.

Martins et al. [24] determined the interfacial friction factor which occurred due to cuttings bed existence during the horizontal transport. Several parameters were tested through this work by varying the fluid, the geometry and the particle factors. Using a 12 m long loop, solids were injected into two typical annular geometries to assure the bed buildup. The flow rates of the fluid were increased in order to enable bed eroding, and measurements were made to record the pressure drop and the bed heights. Theoretical correlations and formulation of momentum equations for two-layer were presented. An accurate interfacial friction factor correlation for cuttings transport was derived through this work. The presented friction factor satisfies the condition of no drill pipes rotation.

Li and Walker [25] tested the sensitivity of directional holes with respect to several parameters affecting the drilling transport. Through mathematical modeling, they analyzed the cuttings bed height. Based on this study, predictions were made for hole-cleaning time with circulation mode, and wiper-trip speed that followed by developing of computer program. Results of their work specified that the volume fraction has a great impact on underbalanced drilling. When the liquid/volume fraction was less than 50%, the cuttings transport was significantly reduced. The most influential variable on cuttings transport in this study was the minimum fluid in-situ velocity. The time required for hole cleaning by the circulation mode showed a non-linear decrease as the fluid flow rate increased. The above-mentioned team extended their work in a subsequent study published in 2000 [26], concentrating upon the evaluation of the influenced cuttings transport parameters, such as cutting particles size, fluid rheology and pipe eccentricity. The effect of the rheology was studied according to the transport flow direction. Analysis of their experimental work indicated that fluid rheology plays a significant role in the hole cleaning. The authors also reported the best way to pickup cuttings is via the low fluid viscosity and turbulent flow. They also recommended that, in order to obtain maximum fluid carrying capacity, a gel or multi-phase system should be used. The position of inner tube was affecting the cutting transport. Better hole cleaning requires more circulation periods, which was found to be critical in order to have a better cost effectiveness.

On 2001 Li and Walker [27] continued their analysis by studying the directional holes cleaning. A computer program was developed in order to predict the cuttings bed height at different angles of inclination. The achieved results strongly supported their previous findings. They suggested that importance of the in situ-velocity emphasizes the need for multi-phase flow correlations that came from empirical data in the issuance of cuttings beds.

Masuda et al. [28]conducted both an experimental investigation and a numerical simulation to determine the critical cutting transport velocity in inclined annuli of arbitrary eccentricity. With specified assumptions, their numerical modeling reflected the interaction between the cuttings and the fluid, which was achieved through use of the two-layer model. Experiments were carried out with water and three different muds in 9 meter long, 5 x 2.063 , and 5 x 2.875 m sections. The behavior of the drilled cuttings at both steady and unsteady states was recorded by video camera in order to capture images to obtain the velocity profile, as well as the cross-sectional distribution and average velocity of cuttings in the annulus. Results from the experimental investigation were contrasted with the numerical model results. Their formulation allowed the fluid and the solid components in the suspension layer to have different velocities, rather than assuming a single velocity for the whole suspension. The results indicated that the match between experimentation and simulation was extremely poor at low cuttings injection rates. Moreover, they concluded that the two-layer model failed to describe the interfacial phenomena involved in the bed dynamics at thin cuttings bed.

Duan et al. [29]carried out an experimental investigation of cuttings transport focusing on the small cuttings sizes (1.3-7.0 mm). Constructing a 100 ft long flow loop with a section of 8 x 4.5 inches diameter. Transport behavior of the smaller cuttings sizes was recognized with both water and polymeric fluids. In addition, correlations were developed to predict the small cuttings concentration and the dimensional bed height. It was observed that smaller cuttings were difficult to transport in water compared to the larger-sized cuttings, while use of Polyacrylic Co-Polymer or, (PAC) solutions facilitated their transport. Furthermore, pipe rotation combined with fluid rheological factors was one of the important parameters in the matter of smaller cutting sizes transport. Further still, it was observed that as flow rate increased the cutting concentration decreased. It was also shown that the hole inclination has only a minor influence on small cuttings transport.

Normally, in each unique case, the application will be different and the procedures which could lead to a successful outcome for one application may lead to the opposite results in another case. Traditionally, the use of correlations and "rule of thumb" are probably not capable of handling the wide range and variety of mud, cuttings, directions and other parameters related to drilling operation and hole cleaning. In addition to the two-phase flow matter, flow through annular geometry and the use of rheological non-Newtonian liquids add more complexity to the problem. This is because of the complicated behavior of these fluids.

By means of experimental investigations, and/or mathematical modeling and computational simulations, researchers have conducted a significant number of studies. Most of the experimental observations have been found to be restricted to a limited range of variables and could not be applied on the wide range of variations. Besides, most of the reported recommendations are related to vertical drilling, which are not valid for directional drilling. Even today, researchers have not arrived at a standard method to practice the different types of non-vertical drilling safely. Repetition of experimental work for the purpose to plan and design the actual fields requires a considerable modification in the flow testing loops, which is not practical.

From an economic point of view, come up with a dependable standard method by issuance and modifications of the experiment loops is mostly unbeneficial.

## 2.3 Mathematical Modeling

In contrast, using mathematical modeling would be more practical in terms of time savings and cost reduction. In this respect, one simple mathematical model cannot be applied from vertical to horizontal orientation. The first challenge of the two-phase system is to define a mathematical model that could adequately integrate the physics involved in this complicated system, noting that solutions of the two–phase flow equations present special challenges beyond those of the single–phase flow. However, by writing of spirit set of complete governing equations which can be solve for each phase, this target may adequately be achieved. Therefore, it is necessary to establish operational procedures by building a precise mathematical model that represents the physics of cuttings transport operation and a procedure generally applicable with the diversity of the available variables and conditions involved. Hence, the proper mathematical system is that one which would go beyond the challenges of describing the core of the phenomena, and should be flexible enough to cover a wide range of variables affecting the phenomena and various interferences between these parameters. Proficient understanding and accurate selection of the correct mathematical approach to formulate the system efficiently are the focal points which may enable the mathematical techniques to simulate the actual phenomena. Definitely, complicated mathematical systems are very difficult to solve directly. Moreover, numerical methods and procedures are notoriously difficult to implement without the assistance of sufficiently useful software [26].

Mathematical modeling based upon an accurate understanding of the physics of the phenomena can be effectively utilized to produce general controllable forms, which can then be applied at the various system conditions. In addition, most of the drilling models are complicated and require numerical methods to be solved.

Therefore, both computer programs and iterative methods are necessary to arrive at accurate solutions in a time effective manner.

In terms of modeling concepts, two distinct categories may be defined. The first category is the mechanistic and empirical engagement modeling. The second category is the layered-modeling approach where special consideration would be given to this section.

### 2.3.1 Mechanistic Modeling

Generally, the mechanistic model is known as a structure that explicitly represents an understanding of physical, chemical, and/or biological processes. Mechanistic models are used to quantitatively describe the relationship between some phenomenon and its underlying first principles or causes. Hence, at least in theory, such models are quite useful for inferring solutions outside of the domain where the initial data was collected, and used to parameterize the mechanisms [30]. Mechanistic modeling is the superior technique for conducting a precise investigation and helpful to deal with/and control this phenomena.

In case of the vertical flow, cuttings fall in the opposite direction of the force of gravity. The contrast between the flow and saltation directions resulted in no bed formation. Thus, all cuttings were supposed to be in suspension and displaying the same behavior. Accordingly, the annular flow in the vertical orientation can be represented as one mixed layer of mud with suspended cuttings. Figure 2.1 shows the mechanism of the single layer in the vertical transport.

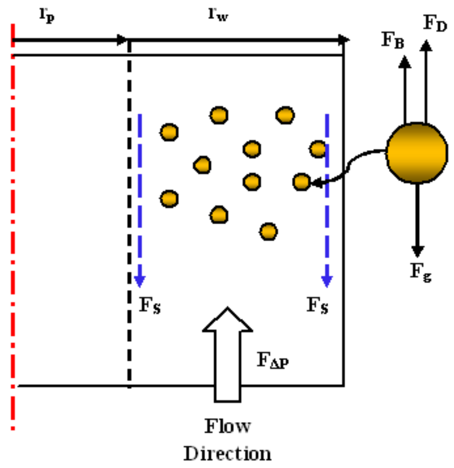


Figure 2-1: Acting forces during vertical annular transport

Observed facts confirm that increase in the wellbore inclination leads to faster accumulation of cuttings, which in turn increases the time required to clean the borehole [31].

In the inclined orientation, the direction of cutting settling is still vertical but the fluid annular velocity reduced its vertical component according to the deviation angle [20]. The common layers of cuttings found in the inclined transport were two distinct layers.

The upper layer consisted of suspended cuttings. This layer has similar behavior as the single layer in the vertical orientation. The lower layer can either be moving-bed or stationary-bed layer. The upper suspension layer was always found to have a very small portion of cuttings concentration compared to the lower layer. Figure 2-2 shows the mechanism on the two inclined layers of transport.

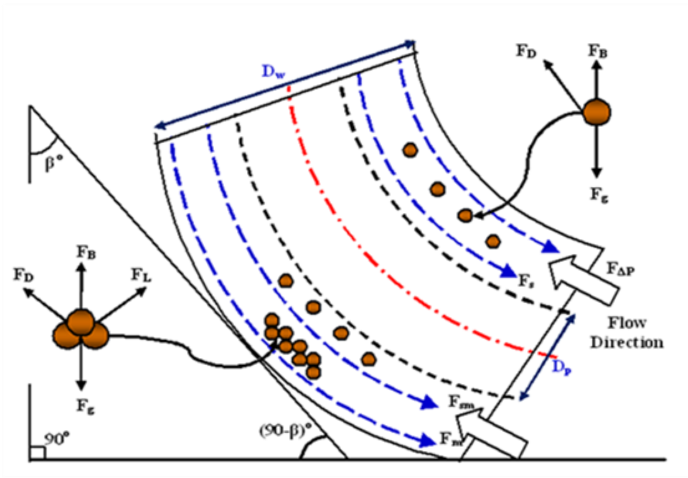


Figure 2-2: Layers and acting forces during deviated annular transport

At high deviated angles up to a horizontal orientation, in addition to the two common layers, a third layer was also observed. Therefore, three distinct behaviors would be observed in the horizontal transport. In this orientation, each particle has a greater tendency to settle down. Clusters of accumulated particles aggregate to form a bed of stationary particles, i.e. dead motion. In addition, acting forces vary between the different layers. An additional force was identified only in the stationary-bed layer of the horizontal orientation. This force is called plastic force which results due to the yield stress of the mud [32]. The mechanism of particles in the three layers is displayed in Figure 2-3.

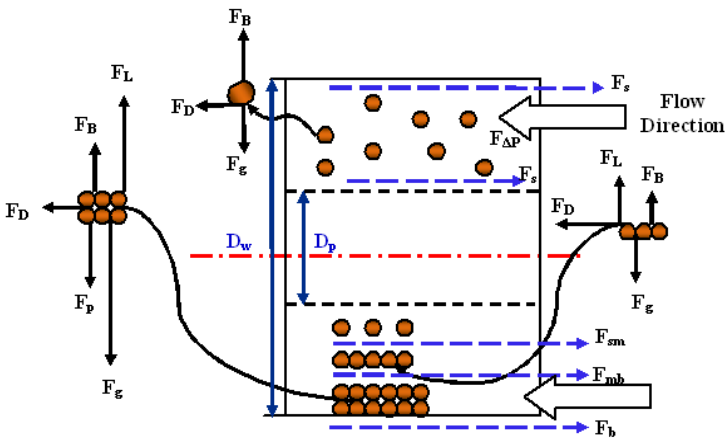


Figure 2-3: Layers and acting forces during horizontal annular transport

When horizontal wellbores become longer and deeper or are used for extended reach, wellbore cleaning becomes increasingly difficult and poses different challenges than are encounter with vertical wells. Moreover, in horizontal wells, the cuttings bed is deeper at high rate of penetration than for low rate of penetration at the same flow rate [27].

Utilize the mechanistic approach some researchers are heavily focused upon the mechanism of force analysis to explain the cuttings particles movement within the carrier fluid during the transport. Clark et al. [32] presented a mechanistic model for inclined cuttings transport. Their model related the mechanism of particle transport in three ranges of angles to three modes of transport. The first one was in the vertical/near to vertical transport, where the settling velocity determined the transport of particles. The second was in the intermediate angles, where the transport of moving bed cuttings can be formed via a lifting mechanism. In the third range of high inclination angles, the transport depended upon the rolling mechanism.

Campos [33] developed two mechanistic models to predict cuttings transport in the highly inclined wells. The first model was classified as two-phase one-dimensional model, while the second one was two-phase, two-dimensional model, which could only be used in the case of cuttings bed absence. Each of the models assumed the same hypothesis of steady states and incompressible flow for the two-phase. However, both of the models can be used to generate some useful information.

Zou et al. [34] attempted to develop a computer package to simulate the cuttings transport in inclined and horizontal wells. They used a mathematical technique following the mechanistic modeling concept. The Bingham-Plastic rheological model was used to signify the fluid phase. The model in this study passed through a comprehensive review of the three-layer model. Eccentricity and rotation were involved to describe the drill pipe condition. The determination of the particles' settling velocity and drag covered a wide range of the particles Reynolds numbers. The calculation of the cutting concentration was carried on the vertical and near to vertical section, while for the inclined section calculations were divided into three parts. Precise software was constructed which operated in Windows environment using Visual Basic. The organized package allows the user to simulate the effect of the operating parameters. It was also able to predict whether the bed was formed or not, and evaluated the hole cleaning process.

Ramadan et al. [35] presented a mechanistic model in order to determine requirements of cuttings flow velocity to achieve successful transport. They analyzed the forces acting upon a bed of spherical particles in an inclined channel. They determined the critical flow rate through equilibrium of the forces. Experimental procedures were conducted in a 4 meter long and 70 $mm^2$ channel section to validate their modeling results. They have accepted most of the results obtained from this model, except those for vertical or close to the vertical orientation. In contrast to the previous studies, the model results were satisfactory. They also found that the critical velocity was influenced by the angle of inclination, as well as by the size of particle in relation to the viscous layer thicknesses and angles.

Duan et al. [36] developed a mechanistic model for sand-sized solids to predict the Critical Re-suspension Velocity or, (CRV), as well as the Critical Deposition Velocity or, (CDV). They investigated the forces acting upon the particles in horizontal and high-angles wells of eccentric annulus. Model predictions were examined with experiments. To somehow the model prediction for CRV and CDV involved some errors. Generally the model they developed was in good agreement with their experimental results. They found that, for smaller particles, the inter-particle force dominated with forces that resist particles movement. They also remarked that water, as drill fluid, was effective in particles bed erosion, whereas the polymer solution was more helpful than water to prevent the bed formation.

Zhou [37] attempted to improve the model previously created by Zhou et al. [38], in which they generated a mathematical model to validate their experimental work for aerated mud transport. However, the modified mechanistic model was developed by means of the two-phase hydraulic equations, the boundary layer theory and the transport mechanism. The new model was capable of predicting bed thickness and minimum transport velocity in inclined and horizontal holes of Under Balanced Drilling or, (UBD) wells. Several transport parameters were studied. The most noteworthy results reported were that large cuttings were harder to clean, and that an increase in fluid density has a positive effect on transport.

The most impressive studies that used the mechanistic modeling approach are summarized in Table 2-1 as follows:

Table 2-1: Targets and outcome of some Mechanistic models studies

| **Researchers** | **Target** | **Outcome** |
|---|---|---|
| Clark et al,1994 [32] | To Investigate the transport mechanism in the three orientations. | In vertical wells, mechanism of settling manages the transport. At intermediate orientation transport depends on the lifting mechanism, where the rolling was the mechanism governs the transport at high inclined angles. |
| Campos, 1995 [33] | To investigate transport of cuttings in directional wells. | The two models feed information but the second one is restricted only in case of no bed. |
| Zou et al, 2000 [34] | To predict formation of cuttings bed and bed height. | Developed computer package to simulate transport. |
| Ramadan et al, 2003 [35] | To Determine the required flow velocity. | Influence by angle, size in relation with viscous layer thickness. |
| Duan et al, 2009 [36] | To Determine the required flow velocity for sand-sized cuttings. | Water is better in bed erosion, while polymers help to avoid bed formation. |
| Zhou, 2008 [37] | To Improve the previous mathematical model of aerated mud transport. | The modified model succeeded in predicting hole cleaning in inclined and horizontal wellbore of UBD. |

### 2.3.2 Layers Modeling

On the basis of the mechanistic modeling concept, the integrated layers modeling approach was launched in the area of transport. As cited by Kamp and Rivero [39], primary layers modeling was practiced to investigate transport in the pipe flow slurries. Meanwhile, the layers concept was introduced to study the annular flow applications. Previously, transport with only two layers had been modeled and was widely used in the field. Tomren et al. [19] observed existence of a third layer during their experiments on the directional cuttings transport. As a result of this observation, the layers concept was extended to address the advanced drilling and transport research. Since cuttings layers concepts were introduced to the directional wells drilling, the layers approach has acquired a very important position in the studies of the particles transport process. There have been a number of research projects that have investigated and modeled the transport operation in directional wells using the layers approach.

As an advanced extension of mechanistic modeling, the layers modeling approach utilized the general strategy for forces acting on each coat of similar cuttings behavior inside the annulus. Solving of multiphase continuity equations and momentum conservations equations for each layer allowed for a closer prediction for the annular flow rates required to remove the drilled cutting particles out of the wellbores.

The three-layer approach is an extension of the layered concept, which has basically been developed on the basis of realistic observation of two-layer during transport. The progress of the layered approach has passed through different stages, up to the recent important observation of the existence of a third layer during directional transport. Thus, the third layer was confirmed and found to behave differently from the other two known layers. In drilling transport studies, researchers and other interested parties have generally claimed that Tomren et al. 1986 [19] was the first researcher who identified the action of three mixed layers during mud annular flow during directional transport.

Whatever the original of the claim, the concept of the three layers states that in the transport process, the sequence of particles flow in a horizontal or near-to-horizontal annulus can be divided into three distinct layers. Each single layer exhibits different behavior and solids concentration. The three-layer distribution as shown in Figure 2-4, from top to bottom is:

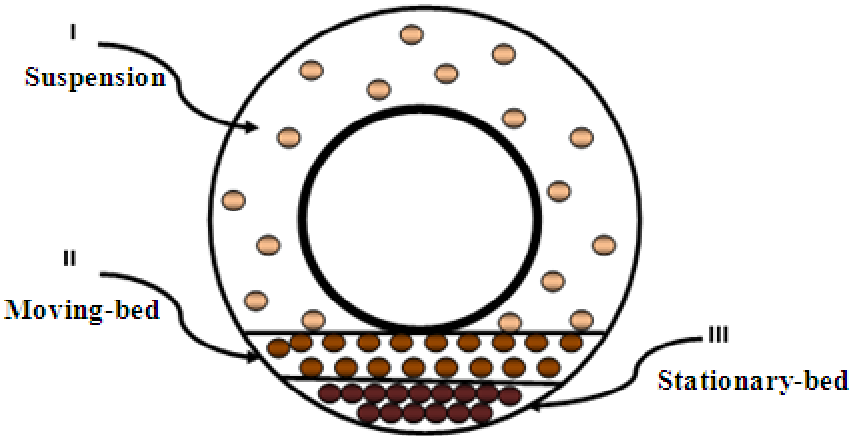


Figure 2-4: The three-layer approach in the annular section

I. Upper: Suspension layer, in which cuttings particles are fully suspended in either a heterogeneous or homogenous flow regime [16].

II. Middle: Moving-Bed layer, in which the concentration is much higher than in the suspension layer. The concentration profile of particles in the moving-bed layer could be assumed to be relatively linear [3].

III. Bottom: Stationary-Bed layer, in which high concentration of settled particles was found in this layer [4].

Gavignet and Sobey [40] conducted one of the first cuttings transport mechanistic two layered models studies. For highly inclined, not rotating pipe and eccentric annuli, two distinct layers were identified. The upper layer was pure fluid and the bottom layer was defined as a compacted bed layer. Their model was built upon the previous models of slurry transportation. Feeding in data from Iyoho [41], comparisons were made between the studies. The authors noted that bed formation in inclined wells must not be predicted on the saltation mechanism, and should instead be determined according to the momentum exchange between the two phases. They also suggested that friction coefficient between cuttings and wall would strongly influence the bed formation. The model results indicated that pipe and particles sizes as well as eccentricity were the most influential variables rather the rate of penetration and rheology. They also recommended the use of large drill-pipe size to prevent bed formation problems.

Martins and Santana [42] published a two-layer mechanistic model for horizontal and near horizontal eccentric annuli. The top layer consisted of homogeneous mixture of mud and cuttings while the bottom layer consisted of compacted cuttings. The model represented a new formulation that draw upon the work of Doron et al, 1987 on sand-water flow in a horizontal pipe. In addition, they also used a dimensionless approach based upon the use of Lokhart-Martinelli parameters. Conservation laws of mass and linear momentum, and constitutive relations describing the interactions between the two phases and between phases and walls were solved simultaneously. Numerical values for unknowns, such as the bed heights, average solids concentration and frictional loss, were calculated based on the flow pattern presented by Iyoho 1980. The results showed that increasing the drill-pipe diameter, the fluid density and the fluid flow rate could effectively contribute in solving of cuttings transport problems.

Walton [17] presented a one dimensional, mechanistic two-layer model. A suspension layer and bed layer with coiled tubing in deviated drilling orientation were studied. He assumed that settling and diffusivity of particles were independent of the concentration. Settling of the particles in this study was formulated in an identical way as used by Doron et al. 1987. A computer code was incorporated to form graphical map to show the flow regime and the minimum suspension flow rate. The simulated model yielded acceptable results compared to the experimental results of Tomren et al. [19]. Based upon the results, the author suggested that moderate-viscosity fluids were more efficient than low and high-viscosity fluids to transport the drilled cuttings. The author also reported that it is more complicated to clean horizontal and deviated wells than vertical ones.

Nguyen and Rahaman [43, 44] carried out series of studies to set a layers hydraulic program for cuttings transport and hole cleaning in an eccentric annulus of highly deviated and horizontal wells. They presented a mathematical model and a geometrical calculator to obtain the required annular section configurations. Their program algorithms fed in results for a range of velocities and various input parameters. The effect of the fluid rheology, the mud weight, the solid density and concentration, the friction coefficients, the pipe eccentricity and inclination were studied in order to inter-relate the effect of these parameters on the cleaning operation. Generally, the simulated results demonstrated the suitability of the layered modeling approach to achieve an effective design of the horizontal and high inclined wells.

Kamp and Rivero [39] utilized the layer approach, and established a preliminary unique two-layer model. In addition to the steady state, they assumed eccentricity and no pipe rotation. They also assumed there is no significant slip velocity difference between the particles and the mud. The upper layer was a heterogynous layer of cuttings and mud, while the bottom layer was the bed of drilled particles. Three mass conservation equations were constructed: one for the cuttings, one for the fluid in heterogeneous layer, and one for the mixture in bed layer. Two momentum equations were built for each separated layer. To solve the system numerically, the boundary conditions were used to define dimensionless quantities those put in matrix forms. Average flux of cuttings and turbulent diffusivity were used to calculate the concentration. Regarding the particle settling, the researchers excluded the influence of the particle hinder behavior, and referred that to the requirement of the diffusion solution. Their results found that an increase in the interfacial shear would lead to the re-suspension and bed velocity. They observed that the dimensionless bed height (as a function of mud flow rate, rate of penetration, mud viscosity, particle diameter, and pipe eccentricity) increased with the particle size, and as a result, they confirmed that transport of small cuttings was considerably easier. Kamp and Rivero also reported that the transport of larger particles was more efficient. In addition, they also reported that increasing the eccentricity increased the bed height. However, their model over predicts the transportation at a given mud flow rate than was actually observed. Therefore the researchers anticipate the possibility of further improvement of their model.

The layered model conducted by Kamp and Rivero [39] to study the transport phenomena in the wellbores excluded the influence of hinder behavior on the particles settling, referring that to the solution requirement of diffusion. However, at a given mud flow rate, their model over predicted the particles transportation.

Feng et al. [45] mentioned that with any type of particulate flow, collision between particles is unavoidable, and this issue should be considered especially when the flow is dense and the particles moves at high a Reynolds number. Accordingly, it could be expected that errors of the two-layer model of Kamp and Rivero 1999 may particularly be caused by neglecting the hinder behavior effect on the particles settling velocity which occurs during the transport.

Santana et al. [46] created a two-layer model for high angles and horizontal wells. The well-known conservation equations of mass, written for solid and liquid phase, were solved together with the momentum equations written for suspension and bed layer. In this study, the accuracy of the assumption of no solid-liquid slip, which was proposed by Martins and Santana [42], was also examined. The pressure gradient was obtained by Darcy's equation for a porous media. The computational implementation of their two layer model indicated that the difference of the obtained results refer to their choices of the rheological model. Accordingly, both models were sensible for rheology parameters. They also verified their use of the interfacial friction factor correlation and reported its impact on the cleaning prediction. Generally, their results proved the reasonability of the no-slip assumption between solid and liquid phase.

As part of the previously mentioned research by Masuda et al. [28] in addition to the experimental study they have studied the transport of the drilled cuttings by simulation procedures. The simulation was performed using the two-layer modeling approach as suspended and moving-bed layers. The mass balance and the momentum conservation have been set based on two-layer regions. Region one was the moving-bed. Region two was the suspension. By solving six equations, the velocities of each layer and mud annular velocity, the bed height, the suspension concentration and the pressure were obtained. They performed comparisons between simulation and experiments, and the results showed that majority of the studied cases were found to match successfully.  However, for the calculated velocities, relatively poor results were obtained.  This demonstrates the limitation of two-layer approach models to predict the transport process.

Cho [4] divided the directional orientation of drilling into three sections and introduced the discipline of the three segments hydraulic model. The three segments were built on the basis of the inclination angles range (0-90$^o$). They developed a three-layer model of cuttings transport which combined with their new derived concept of segments. An eccentric annular section with coiled tubing drilling was detailed in this study. An analysis of the forces acting upon cuttings layers was carried out, based on the continuity and Navier Stokes equations, in addition to broad analysis of the annular velocity, pressure gradient and fluid rheology. Six equations of six unknowns were solved numerically, and a computer program was built in order to be utilized in the planning steps of drilling. They reported effects of the annular velocity, the fluid rheology, and the angle of inclination on the cuttings transport. The results showed good agreement with experimental data which had been obtained by others.

Ramadan et al. [3] applied a three-layer model on horizontal and inclined channels. Transport of spherical-shaped particles through 70 mm pipe diameter was determined in the context of certain assumptions. The study utilized the pseudohydrostatic pressure concept in a wide range of the analysis. The concept was repeatedly utilized in several parts of their model. It was used to approximate the dry frictional force, to estimate the normal force between the wall and the bed layer, as well as to model the moving bed thickness. For the inclined pipe flow, numerical producers were issued to solve a set of eleven equations, hoping to obtain estimated values for eleven unknowns. The equations were solved simultaneously, and the results reflected the reasonability of the layers-model approach. Very thin moving-bed layer became thicker with increasing flow rate. This study encountered various criticisms from Stevenson [47], who commented that authors a parented had overlooked an earlier study by Doron and Bernea on 1997. Stevenson claimed the model described by Ramadan et al was identical to the model by Doron and Bernea 1997. However, the authors responded to Stevenson's comments and strongly defended the unique features of their model. Frankly, Ramadan et al. [48], have illustrated the confusions involved in the study and replied to the criticisms to justify their model findings. However their three-layer application was impressive despite of that investigation was not on drilling transport mainly since they haven't considered the drilled cuttings size, cuttings shape as shown in Figure 2-5 or either annular space.


Figure 2-5: Irregular particles shape [2]

Various empirical factors were employed in order to describe the shape of man-made particles. Those efforts provided some empirical description by identifying the parameters of the particle's characterization, such as volume, surface area, projected area and projected perimeter. Selection of the shape factors should be handled with further awareness to their relevance. Wadell 1933 [49] suggested the important concept of spheristy to describe the irregular shaped particles. However Sphericity of crushed sandstone varies between 0.8-0.9 [50], and drilled cuttings sphericity ranges between 0.75-0.85 [4].

Doan et al. [51] described a simulation of cuttings transport for eccentric annuli in Under Balanced Drilling Or, (UBD). It was arbitrarily assumed to have either vertical or horizontal orientation rather than any specific inclination. The model was examined under different conditions, including an unsteady state. Compared to the experiments conducted, the calculated cuttings velocity was in reasonable agreement with what was measured. However, there was a poor match between the measured and the predicted results of dilute cuttings injection rates. Even so, this strongly reflects the weakness of the two layers model approach in the issue of describing the interfacial phenomena.

Naganawa [52] described a modified two-layer model of cuttings transport that enabled more practical use of their simulator. Modification was carried out in order to enable the model simulation to cover more particles on the directional wells trajectories. The extended model was capable of describing the behavior of the relatively low inclination wells. In order to evaluate the model, post analysis of hole cleaning for actual Extended Reach Well or, (ERW) in Japan was handled by the new simulator. Output of the simulations for the modified two-layer model produced successful results for the transition behavior of cuttings over the hole trajectory.

Costa et al. [53] used a two-layered model to simulate the transit cuttings transport and Equivalent Circulation Density or, (ECD), in the wells drilling. Their model assumed a steady states flow, pipe eccentricity and sphericity of particles. The two-layers represented an upper suspension layer and a bottom bed layer with 52% solids concentration in the bed. Power low fluid was employed to simulate properties of the liquid phase. Mass conservation of the separated phases, momentum conservation for the separated layers, and other equations for shear stress and friction factor correlations for both laminar and turbulent flow were stated. Using Carten's 1969 relation the mass diffusivity was determined. The established numerical computational system was solved using the finite element method, where Newton-Raphson techniques of equation's linearization were also utilized. The results demonstrated the capability of their technique to estimate the bed height, the cuttings concentration, as well as the pressure and the ECD observed variations. They reported the influence of the ROP on the bed formation and pressure distribution in the well. The influence of the cuttings concentration on EDC profile was also reported. Despite the need for further development, their two-layer model was computationally effective.

The various studies which used the two- and three-layer models are summarized in Table 2-2 and 2-3 respectively.

Table 2-2: The two layers models.

| Researcher | Layers |
|---|---|
| Gravignet and Sobey, 1986 [40] | Mud-bed |
| Martins and Santana, 1992 [42] | Homogenous mixture-bed |
| Walton, 1995 [17] | Suspension- bed layer |
| Kamp and Rivero, 1999 [39] | Heterogynous-bed |
| Santana et al, 1998 [46] | Suspension-bed layer |
| Masuda et al, 2000 [28] | Suspension- moving-bed layer |
| Doan et al, 2003 [51] | Suspension-bed layer |
| Costa et al, 2008 [53] | Suspension-bed layer |

As an extension of the segments concept created by Cho [4], Cheng and Wang [54] presented a three-segment hydraulic multi phase model. Foam was employed as the main drill fluid while gas was used as a third phase in horizontal drilling. Based on two critical inclination angles, Cheng and Wang used the power law rheological model to represent the fluid viscosity. They considered the two phase (fluid and solid phase) only in the built-up of continuity. In addition, the one dimensional diffusion equation was used in order to solve the concentration question. To somehow their simulation output compared to the drilling practices was exhibited incorrect behavior. Thus, the results showed an over estimation compared to the experimental results of Capo [55].

The following table summarizes the highlighted studies of cuttings transport which were conducted in the light of the three layer approach:

Table 2-3: The three layers models.

| Researcher | Orientation | Conduit features |
|---|---|---|
| Nguyen and Rahaman, 1996-98 [43, 44] | highly deviated and horizontal | Eccentric annulus |
| Cho [4] | Horizontal and Deviated | Eccentric annulus |
| Ramadan et al. 2005 [3] | Highly Inclined & horizontal | Channel/pipe flow |
| Cheng and Wang, 2008 [54] | Horizontal and inclined drilling | Multi phase in eccentric annulus |

## 2.4 Computational Fluid Dynamics CFD

The Computational Fluid Dynamics or, (CFD) methods involve revaluation techniques in the area of simulations. Through the use of these methods, highly sophisticated and detailed analyses of many engineering problems became possible. The use of CFD in different areas as a simulation tool demonstrated its capability as an exclusive measurement for examining a field's process and providing bundles of valuable information. Since predicting of the processes applicability is necessary to judge weather is it difficult or impossible to achieve the targets, CFD can be employed as a forecasting tool without expensive hardware [56]. Recently, CFD simulation techniques have been introduced into the field of solids transport studies. CFD software became necessary for the concerned parties in order to ensure process improvement in the plant applications, such as pneumatic transport lines, risers, fluidized bed reactors, hoppers [57].

Ali [18] was the first researcher who studied and analyzed the cutting transport parameters using CFD. He have applied hole cleaning simulation using the Discrete

Phase Modeling (DPM) in FLUENT and conducted the analysis for horizontal and vertical wells. He judged the qualities of the hole cleaning through the transport efficiency. The effect of the mud flow rate, mud weight, mud viscosity, drilling rate, cutting size and cutting density were analyzed. Relative deviation between the model prediction and the experimental data was observed at high velocities, and this was related to difference of the cuttings sizes tested in each case. Ali's results indicated the importance of the annular velocity in cuttings removal. He also reported that horizontal well cleaning was better than for vertical wells.

It was eventually noticed that some of the researchers' findings obtained through CFD did not closely correspond to observable reality since those results do not match either physical facts or valid results which obtained from both experimental work and numerical procedures e.g. [17, 27, 35].

Another CFD technique used to investigate steady state cuttings transport in horizontal and deviated wells was employed by Mishra [56]. Instead of DPM, Eulerian Mixture Modeling capabilities in FLUENT software were used in the study. The parameters this study was concerned with the fluid flow rate, ROP, angle of inclination, drill-pipe rotation and cutting size. The results indicated that fluid flow rate, angle of inclination, and ROP have a major impact on the cutting concentration. Furthermore, they recorded that larger particles were more efficiently cleaned, and pipe rotation would greatly enhance the hole cleaning, especially for the smaller sizes.

Once again, the CFD results were noted to be in conflict with the experimental and analytical works, where it has been repeatedly demonstrated that smaller particles are indeed easier to clean, as noted in [26, 39, 58]. This is especially in the cases where pipe rotation is involved. Even so, we can compare Mishra's results to the claims of Wilson and Judge on 1978, who have also claimed that smaller particles are harder to clean than larger one. The particle sizes used in the study by Mishra were within the given range of the easiest removable sizes cited in [26].

The nature of the available commercial software in its simplest practice is still inconvenient since it lacks to capture some facts. This may refer to incapability of this soft ware to own some features involve in the transport phenomena such as the layers. However, both CFD simulations were unique to studies of the cuttings transport phenomena

## 2.5 Summary of Previous Work

In essence, direct information and sufficient recommendations were utilized to satisfy the requirements of cuttings transport in vertical drilling. In contrast, directional drilling practices still facing problems and conflicting opinions about some of important variables, such as effect of the particle size. Therefore, further consideration should be given to this type of directional transport. Bed tumbling and sliding in inclined drilling transport and high bed formation in horizontal transport are critical problems. Moreover, additional attention must be devoted to the long-horizontal wells in which deeper beds may form and serious transport problems might be encountered [17].

Due to the static force resulting from the absence of the essential force that overcomes the gravity during the horizontal transport, the buildup of cuttings bed is strongly enforced. As a result, the complex turbulent flow becomes necessary to create the turbulent eddies required to achieve the transport, which causes additional difficulty for horizontal drilling.

The use of experimental observation only does not permit assessment of wide variation among the variables that affect the cuttings transport. With the respect to the outcome of empirical models, experimental results from specific field inputs data and conditions will no longer be useful for the high diversity of cases that are encountered. This issue may restrict the outcome in a narrow range, and limit the outcome into the typical or closer sets of conditions. Seeking an accurate understanding of a different field data or wider range of cases requires continuous experiments, more duplication and many loop modifications in order to satisfy the requirement of new set of conditions with which the researchers are confronted. Since such efforts and very time consuming and expensive, the means experimental work has some limitations.

Nevertheless, investigation of the transport problem with mathematical models has been anticipated to able to handle a broad range of variations. Modeling techniques facilitate the simplification of the complex interactions that exist between variables that need to be studied under many different conditions. The opportunity of model development and modification gives this technique a greater possibility for application. In addition, the relative ease and flexibility of applying models upon a very diverse range of cases and materials also ranks such modeling techniques as being superior to actual experimentation. These models could be precisely and cost-effectively applied to different angles, fluids, cuttings and other variables.

In addition, several modifications were constructed for the two-layer model after observations of its deficiency in order to match with the mechanism of cuttings transport [28]. This led to a more adequate modeling approach, which was then able to distinguish between three different mixer behaviors during the transport, i.e. the three-layer approach. Even so, at least some of the phenomena formulation may need some empirical facilities to be adopted and embedded in the models.

Therefore, from the literature survey, it can conclude that:

- Still there is some ambiguity in the area of directional wells that requires more investigation to increase the efficiency of this style of drilling.

- Problems of transport as tool blockages and cutting's bed formation are associated with horizontal drilling orientations. Significant reduction of the transport capacity is more expected in the horizontal wells.

- Mathematical techniques were more capable to produce general applicable concepts and principles. They are flexible methods which facilitates extraction of the facts for the various cases and scenarios encountered in the field with time and cost effectiveness

- In many instances, the two-layer approach has failed to describe the directional transport phenomena [19, 28, 53]. In contrast, the three-layer approach has become a more widely accepted means of modeling what occurs during the transportation of drilled cutting particles, particularly during directional and horizontal cleaning.

- Many of the previous research efforts did not involve the sphericity effects.

- Using the three-layer, studies [4, 43, 44, 54] have followed similar considerations for the eccentric of annulus in spite of the disadvantages of this condition.

- With CFD, it has been observed that using of the simplest conditions in the commercial software (FLUENT) was impractical. Thus, the commercially-available software still requires a considerable amount of modification and improvement, even beyond its accessibility by the User Define Function tool or, (UDF), in order to perform a better analysis of the drill cuttings transport process.

# Chapter 3

# Research Methodology

## 3.1 Introduction

Since the first introduction of the layers-model approach, which was based on mechanistic theorem to describe the process of annular cuttings transport, significant progress has occurred the field of the analytical modeling. These advances have led to a deeper understanding of how drilled cuttings move within the drill mud flow, as solid-in-liquid two-phase flow.

As cited by Cho [4], Doron et al. argued that two-layer models are not capable of describing the mechanism of cuttings transport. This is because such models lack the ability to predict the existence of the stationary-bed. Furthermore, as pointed out by Kamp and Rivero [39], the two layer model has proven itself to be unable to represent the cuttings transport process in both horizontal and near to horizontal wells. Similarly, this fact has also been confirmed by the study carried out by Masuda et al. [28] and partially through the by Duan et al. [36].

In this section, the proposed mathematical model applied by Ramadan et al. [3] for a channel flow was extended to the horizontal annular flow of drilled cutting particles. In fact, their work was not directly related to the cutting transport in drilling operation. Hence, in this study, the three-layer model would specifically be used to investigate the cuttings transport performance in the annular geometry of well, with much consideration to several vital factors that affect the cuttings transport process. These factors would include the particles shape, the particle size, the fluid viscosity, the annular size and the rate of penetration in concentric drilling. Besides, the frictional factors effect would also be inspected.

### 3.2 Model Hypotheses

Informed by an awareness of conservation laws of mass and momentum principals, a three layer model was developed for horizontal cuttings transport in annular flow. The model was mainly targeted to predict cutting bed heights, pressure drop, and transport velocities. The following hypotheses were used in the current model:

➢ Flow states

- Steady state ( $\partial / \partial t = 0$ ).
- Incompressible ( $\rho_f$ = constant).
- Turbulent flow ( $\mathrm{Re}_f > 2400$ ).

➢ Drilled cutting particles

- Cuttings size was represented by mean particle diameter, and cuttings shape was represented by sphericity.
- Particle distribution in the suspension layer is approximately uniform, linear in the moving-bed layer and uniform with constant value in the stationary-bed layer.
- Volumetric concentration in each layer is uniform along the well length.
- Rolling effect is negligible.

➢ Carrier/drilling fluid

- Drilling mud is a non-Newtonian fluid and will be modeled as power- law fluid.
- Rheological properties and density of fluid are constants.

➢ Drill-pipe conditions

- Concentric.
- No rotation.

➢ Other hypotheses

- Two-phase solid-in-liquid flow.
- The process is adiabatic.
- No slip condition. According to [42]Martins and Santana and [48].

### 3.3 The Mathematical Model formulation

Transport of heterogeneous mixer of non-Newtonian fluid and drilled cuttings in annulus is based on the fact that mud flow with cutting particles in horizontal transport results in three layers, where each layer displaying different behavior. Hence, the transport phenomena, under the previous mentioned can be illustrated mathematically through set of equations as follows:

#### 3.3.1 Mass Balance

The mass transport equation for a one-dimensional, two-phase, horizontal flow in an annular element of length *z*, under steady states can be written in general terms for the unit length *dz* as follows:

$$\frac{\partial}{\partial z}\left(\rho_x c_x U_x . A_x\right) = 0 \tag{3.1}$$

Recall the hypothesis of no-slip condition between solid and liquid phase, the continuity equation for the solid-phase could be written as:

$$\frac{\partial}{\partial z}\left(\rho_s c_s U_s A_s + \rho_m c_m U_m A_m + \rho_b c_b U_b A_b\right) = 0 \tag{3.2}$$

Integrating the previous equation returned the continuity for the solid phase as follows:

$$U_s c_s A_s + U_m c_m A_m + U_b c_b A_b = U_a c_t A_a \tag{3.3}$$

In addition, the continuity equation for the liquid phase can be calculated as:

$$U_s (1 - c_s) A_s + U_m (1 - c_m) A_m + U_b (1 - c_b) A_b = U_{av} (1 - c_t) A_a \tag{3.4}$$

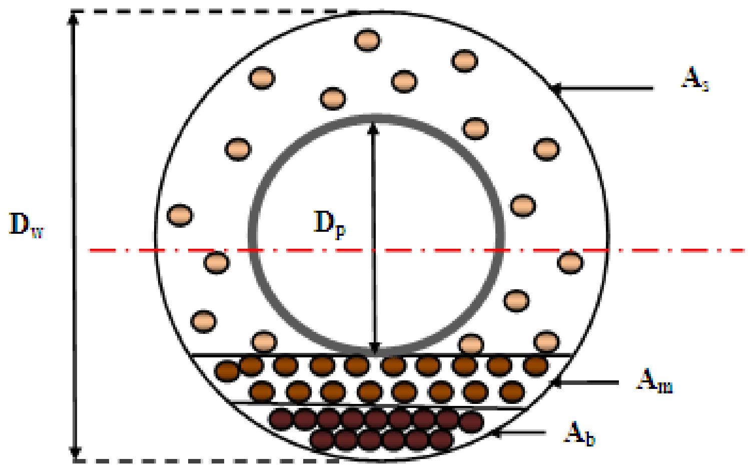


Figure 3-1: Dimensions of the annular section

In a horizontal orientation with three layers, the total annular area is $A_a = \pi/4\left(D_w^2 - D_p^2\right)$. As shown in Figure 3.1, the annular area also can be defined as the sum of the three layers cross-sectional area:

$$A_s + A_m + A_b = A_a \tag{3.5}$$

The total cuttings volumetric concentration can be specified as a function of the average rate of penetration or, (ROP). Under steady state conditions, the total concentration created by the drill-bit is given by the equation [43]:

$$c_t = \frac{ROP}{U_a\left(1 - \left(\frac{d_{pipe}}{D_{hole}}\right)^2\right)} \tag{3.6}$$

### 3.3.2 Momentum Balance

The momentum analysis was written according to the diverse layers. Accordingly, three momentum equations are involved to describe the suspension layer, the moving bed layer and the stationary bed layer.

#### *3.3.2.1 Momentum for the Heterogeneous Suspended-layer*

The upper layer is relatively pure fluid or heterogeneous mixer of non-Newtonian fluid and drilled solids. It is important here to mention that all forces in the momentum balance are based on a unit length *dz* =1.

The forces applied to the fluid in this layer were: (a) the pressure, (b) the shear forces at its wall, and (c) the shear at the tangency with moving-bed layer. Considering a steady state condition, the force acting upon the horizontal flow per unit length, shown in Figure 3-2, could be specified by:

$$-A_s \frac{dp}{dz} - \tau_s S_s - \tau_{sm} S_{sm} = 0 \tag{3.7}$$

Which is corresponding to the form (Pressure forces=∑shear forces).

The shear stress between the upper layer and the wall surface resulted from the contact between the well walls and the pipe wall. This shear is defined by [59]:

$$\tau_s = \rho_s f_s U_s^2 / 8 \tag{3.8}$$

At the interface between the upper suspension layer and the moving bed layer below it, the shear stress is given by [3]:

$$\tau_{sm} = \frac{1}{8}\rho_s f_{sm}(U_s - U_m)^2 \tag{3.9}$$

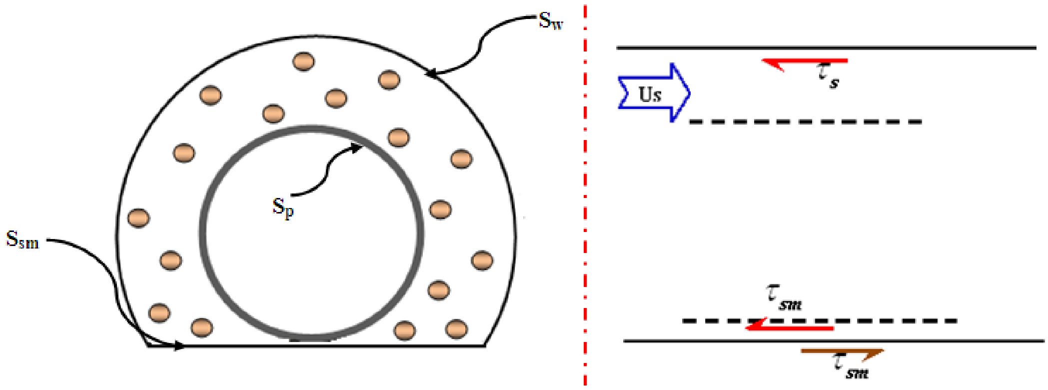


Figure 3-2: The exerted shears in the annular suspended-layer

Since the flow in the suspension layer is heterogeneous, the effective layer density is calculated from [4]:

$$\rho_s = c_s \rho_p + (1 - c_s)\rho_f \tag{3.10}$$

Turbulent flow is still complex even for Newtonian fluids flows in quite simple geometry. Moreover, accumulation of particles in this type of flow will result in complex, unsteady motion and distribution of particles [16]. Therefore, the calculation of a Reynolds number in turbulent, non-Newtonian liquid, attached with particles in annular flow, will became more complicated.

Calculation of a Reynolds number is a preliminary and essential step to classifying the flow type, and consequently necessary to calculate the friction factor.

Here, a generalized Reynolds number for the suspension layer under the power low model can be written as:

$$\mathrm{Re}_{gs} = \frac{8\rho_s U_s^{(2-n)} D_h^{\,n}}{K_s}\left(\frac{6n+2}{n}\right)^{-n} \tag{3.11}$$

Where $n$ is the flow index behavior and $K_s$ is the adoption of the fluid consistency index $K$ and the concentration $c_s$. Considering the concept provided by Einstein 1906for solid volume fraction $c_s < 0.01$ [60], the suspension layer viscosity will be calculated according to:

$$K_s = K(1+2.5c_s) \tag{3.12}$$

Many correlations were suggested to derive the friction factor in the turbulent two-phase flow. Some of the available correlations used in studies of cuttings transport included the features of non-Newtonian power low fluid to evaluate the friction factor. It can be observed that most of studies used Televantos correlation[2] because of its simplicity, such as in [42, 51, 53, 54]. It has been claimed by Martins et al. [24] that this correlation does not provide specific accuracy for the annular geometry and the non-Newtonian fluids behavior effect simultaneously. Reference [3] used another correlation, which was proposed by Szilas et al.[3]. This correlation matches the finding of the friction factor in both smooth and rough walls, two-phase flow and the explicit power low behavior:

$$\frac{1}{\sqrt{f_s}} = -2\log\left(\frac{10^{-\lambda/2}}{\mathrm{Re}_{gs}\, f_s^{(2-n)/2n}} + \frac{d_p}{3.71D_h}\right) \tag{3.13}$$

While the constant $\lambda$ depends upon the index behavior and is related as following:

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[2] Citied in [42], [51], [53] & [54]
[3] Cited in [3]

$$\lambda = 1.151^{\frac{1}{n}}\left(\frac{0.707}{n} + 2.12\right) - \frac{4.015}{n} - 1.057 \qquad (3.14)$$

As cited in [3], Doron and Barnea suggested that the interfacial friction factor between the two layers will be accounted as twice the wall friction factor:

$$f_{sm} = 2 f_s \qquad (3.15)$$

As stated in the literature, the friction factor for the turbulent flow could be predicted by other correlations. In parallel, Cho [4] and Cheng and Wang [54] have constructed their mathematical models using a three-layer approach and agreed with the use of the empirical relations shown below to calculate the friction factors in the boundary of the upper layer. (a) Correlation by Doron and Barnea 1993 for suspension:

$$f_s = 0.00454 + 0.645\mathrm{Re}_s^{-0.7} \qquad (3.16)$$

(b) The correlation by Martin et al 1996 [24] for the interface between suspension and moving bed layers:

$$f_{sm} = 0.966368\mathrm{Re}_s^{-1.07116}\, n^{2.360211}\left(\frac{d_p}{D_{hs}}\right)^{-2.34439} \qquad (3.17)$$

These methods to predict the friction factor in the layers have been implemented in two different simulation models of cuttings transport in order to highlight the difference between them.

### *3.3.2.2 Momentum for the Moving-bed Layer*

Referring to Figure 3-3, the sum of the forces per unit length on the moving-bed layer is given by the following momentum equation:

$$-A_m \frac{dp}{dz} + \tau_{sm} S_{sm} - (\tau_m S_m + F_d) - (\tau_{mb} S_{mb} + F_{mb}) = 0 \tag{3.18}$$

The shear stress between the moving-bed layer and the well boundary is:

$$\tau_m = \rho_m f_m U_m^2 / 8 \tag{3.19}$$

The interface shear between the moving-bed layer and the stationary-bed layer is:

$$\tau_{mb} = \frac{1}{8} \rho_m f_{mb} (U_m - U_b)^2 \tag{3.20}$$

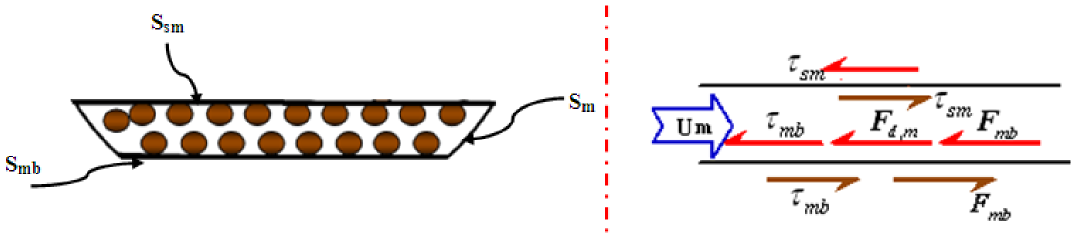


Figure 3-3: The exerted shears in the annular moving-bed layer.

Equation (3-13) will be used to calculate the friction factor in the middle moving-bed layer. In case of laminar flow other correlations sould be use. Televantos et al. 1979 recommended that the dispersive force will take care of the dispersive shear stress between the moving-bed and the stationary-bed layers. Therefore, to account for the friction factor between the moving-bed and the stationary-bed layer, the same value of the friction factor between the moving-bed layer and the walls will be considered, [3]. Hence:

$$f_m = f_{mb} \tag{3.21}$$

Furthermore, the following empirical equation by Dorn et al 1993 for moving-layer and for the interface with a stationary bed will be examined:

$$f_{mb} = 0.046\,\mathrm{Re}_m^{-0.02} \tag{3.22}$$

The effective density for the moving-bed will be:

$$\rho_m = c_m \rho_p + (1 - c_m)\rho_f \tag{3.23}$$

The dispersive shear stress between the moving-bed and the stationary-bed layer has important implications for the present model. Thus, the previously mentioned shear would give an impressive indicator about the formation of the third moving-bed layer in the middle. The dispersive shear can be represented by the following relation:

$$\tau_{dis} = \frac{F_{mb}}{S_{mb}} \tag{3.24}$$

Indeed, the concept of pseudo-phenomena is a common application in many of the engineering mathematical applications, as employed in [61].

Ramadan et al. [3] used the pseudohydrostatic pressure distribution to approximate an equation for the dry friction force between the moving bed and the wall boundary. Considering Figure 3-4, their estimated dry friction force formula for the horizontal orientation was as indicated below:

$$F_d = g\mu_d \left(\rho_p - \rho_f\right) c_m S_m t_m \cos\left(\frac{\theta_b + \theta_m}{2}\right) \tag{3.25}$$

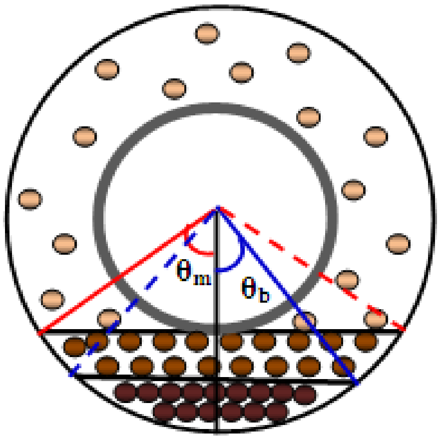


Figure 3-4: The angular bed layers thicknesses

A study by Nguyen and Rahaman [44] approximated the dynamic friction coefficient to be half of the static coefficient relating their value to each other. Therefore, a similar manner and value will be imposed in the current model, as following:

$$\mu_d = \frac{\mu_s}{2} = 0.2 \tag{3.26}$$

This value of the friction coefficient seems high, but should bear in mind that this is for solid-in-liquid two-phase flow.

*3.3.2.3 Momentum for the Stationary-bed Layer*

The forces in Figure 3-5 represent the momentum equation for the bottom stationary-bed layer given by:

$$-A_b \frac{dp}{dz} + \left(\tau_{mb} S_{mb} + F_{mb}\right) - \left(\tau_b S_b + F_b\right) = 0 \tag{3.27}$$

Where:

$$\tau_b = \rho_b f_b U_b^2 / 8 \tag{3.28}$$

The effective stationary bed-layer density is given by:

$$\rho_b = c_b \rho_p + (1 - c_m)\rho_f \tag{3.29}$$

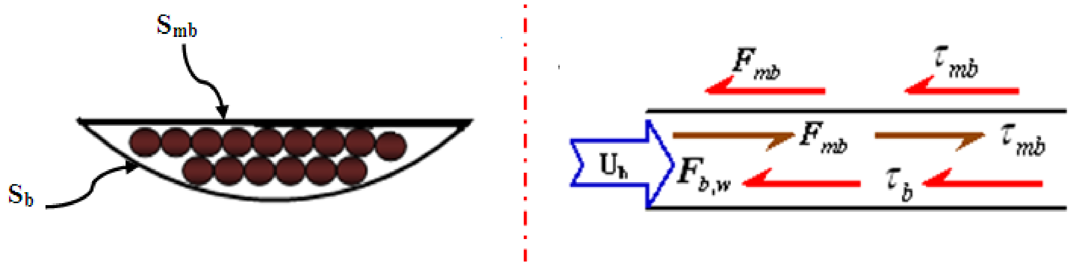


Figure 3-5: The exerted shears in the annular stationary-bed layer

### 3.3.3 Analysis of the Moving-Bed Layer

Inclusion of an additional formula to calculate the moving-bed thickness is necessary in the model set-up. The importance of the layer thickness calculation goes beyond the purpose of checking the existence of the third layer during the horizontal cuttings transport. This formula also helps to determine whether the observed middle layer will either increase or decrease during the transport. Furthermore, this formula validates the approach of the three layers. The formula used by Ramadan et al. was [3]:

$$t_m = \frac{\tau_{dis}}{c_b g(\rho_p - \rho_f)\tan\phi_D} \tag{3.30}$$

Where, dynamic friction factor tan$Ø_D$, of the equivalent dynamic friction angle $Ø_D$ was estimated experimentally by Bagnold 1954 to have a value of approximately 0.75 [62].

### 3.3.4 Mean Velocity of the Moving-Bed Layer

Fredoe and Deigaard [63] defined the velocity profile for the moving-bed layer relative to the bed as follows:

$$U_{d,r}(y) = \frac{U_\tau}{k} 2\sqrt{\frac{2y}{t_m}} \tag{3.31}$$

While the definition of the friction velocity $U_\tau$ is given by:

$$U_\tau = \sqrt{\frac{\tau_{sm}}{\rho_s}} \tag{3.32}$$

Averaging the moving-bed velocity profile over the layer thickness is returned the following mean moving-bed layer velocity:

$$U_m = \frac{4\sqrt{2}}{3k}\sqrt{\frac{\tau_{sm}}{\rho_p}} + U_b \tag{3.33}$$

Substituting the shear $\tau_{sm}$ as given in equation (3-9) and re-arranging the equation (3-33) according to Doron and Barnea concept returns the mean moving-bed velocity as a function of the suspension and bed layer velocities, as the following:

$$U_m = \frac{U_b + U_s \frac{2\sqrt{2}}{3k}\sqrt{\frac{\rho_s f_s}{\rho_p}}}{1 + \frac{2\sqrt{2}}{3k}\sqrt{\frac{\rho_s f_s}{\rho_p}}} \tag{3.34}$$

### 3.3.5 Average Concentration of the Moving-bed layer

To predict cuttings concentration on the moving bed-layer, Fredsoe and Deigaard [63] suggested the assumption of linear variation for the dispersed layer. By adopting the pseudohydrostatic gradient, the average concentration of the moving-bed layer can be approximated as follows:

$$c_m = \frac{c_s + c_b}{2} \tag{3.35}$$

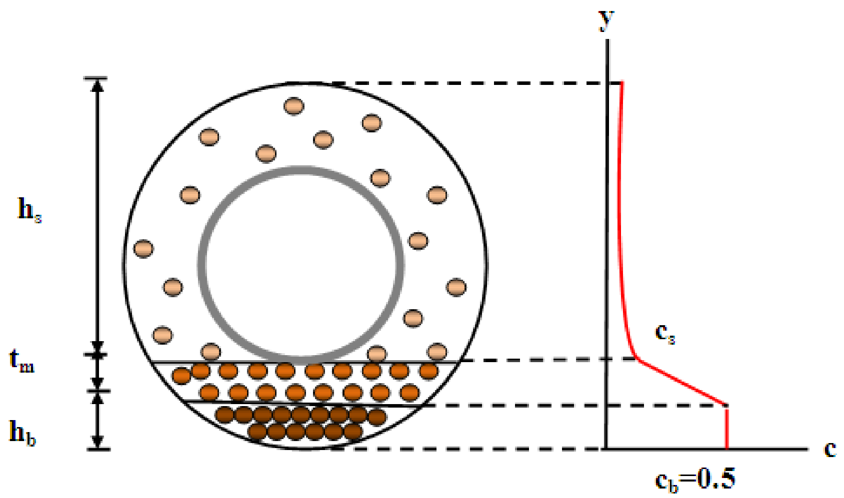


Figure 3-6: The approximated concentration profile for the three-layer by Ramadan et al. [3]

As shown in Figure 3-6, the concentration in the suspended layer is very low in contrast to the moving and stationary bed layer, where the particle aggregation is high. By both experimental and statistical methods, the bed concentration is found to have the range value (0.48-0.52) [4]. Hence, in this study, the solid bed concentration was taken as $c_b \approx 0.5$.

### 3.3.6 Convection-Diffusion Equation

The convection-diffusion equation describes a physical phenomenon of particles or energy transfers in a certain system due to two different processes, the convection and the diffusion. One-dimensional, time dependent convection-diffusion equation is normally written as:

$$\frac{\partial c_{sl}}{\partial t} = \frac{\partial}{\partial y}\left[\Gamma \frac{\partial c_{sl}}{\partial y} + v_s c_{sl}\right] \tag{3.36}$$

The first term in the brackets represents the diffusion, while the second term represents the convection.

To acquire the local concentration of the suspension layer, the convection-diffusion equation is implemented to fulfill the steady state condition. As a result, the equation became:

$$\frac{\partial}{\partial y}\left[\Gamma \frac{\partial c_{sl}}{\partial y} + v_s c_{sl}\right] = 0 \tag{3.37}$$

The above expression specifies that either the first term or the second term is equal zero. Yielding the first term returned the equation:

$$\Gamma \frac{\partial\ c_{sl}}{\partial y} = \left(- v_s c_{sl} s\right) \tag{3.38}$$

According to the convection-diffusion hypotheses, this equation could not be applied to the moving-bed layer. This is because of the settling effect due to collision. Hence, in the present case, the equation was applied to the suspended layer. Consequently, the distance *y* represents the elevation above the interface between moving-bed and suspension layers.

Assuming a constant diffusion coefficient and settling velocity, the average concentration of the suspension layer was approximately estimated in [3] as the following:

$$c_s = \frac{c_m}{h_s} \frac{\Gamma . \left(1 - e^{-\left(\frac{v_h}{\Gamma}(hs)\right)}\right)}{v_h} \tag{3.39}$$

Where the turbulent diffusivity coefficient of particles in the suspension will be calculated by the below formula:

$$\Gamma = kU_\tau \left(1 - \frac{y}{h_s}\right) y \tag{3-40}$$

To avoid zero diffusivity, the distance *y* is recommended to be taken in a very short range. Ramdan et al. [3] estimated the distance *y* as a function of the thin middle layer thickness ($y=t_m/100$). In this study, it was decided to consider this value as recommended by Fredsze and Deigaard [63] to have twice the value of the particle mean diameter ($y=2d_p$) which makes more sense to the presence of physical geometry. Accordingly, the final expression of the turbulent diffusivity became:

$$\Gamma = k(U_s - U_m)\sqrt{0.5 f_{sm}} \left(1 - \frac{2d_p}{h_s}\right) d_p \tag{3-41}$$

### 3.3.7 Cuttings Settling Velocity

The characteristic size, shape and density of a solid particle greatly influence its dynamic behavior in the flowing media. Some of the previous studies assumed a uniform sphere shape when studying the solids transport phenomena [3]. Apparently almost all man-made and natural solid particles have a non-spherical shape. In addition, it is well known that the drilled cutting particles created by drill-bit tools will never have regular shape. Therefore, this assumption might distort the obtained results and limits their usefulness and will never allow predicting the phenomena accurately.

Various empirical factors were employed in order to describe the shape of man-made particles. Selection of the shape factors should be handled with further awareness to their relevance. Thus, Wadell 1933 [49] shape factor that described the degree of particle sphericity $\varphi$, as deviation of the irregular particle shape from the true sphere. Wadell did this through the following ratio:

$$\varphi = \frac{\text{surface area of a shpere of equivalent volume as particle}}{\text{surface area of particle}} \tag{3-42}$$

This relation emphasizes that the factor of the regular sphere has a maximum value of 1, while for non-regular shaped particles the sphericity value will be less than this value. The drag coefficient of a spherical solid particle moving in a fluid is less than that for an irregularly shaped particle. This implies that settling behavior would occur faster for the spheres rather than for irregularly shaped particles. Hence, usage of the sphericity concept increases the reliability in the modeling of drilled cuttings transport.

Therefore, the proper selection of the most suitable formulas in the mathematical modeling will enhance prediction of the critical factors effects. Between the several empirical relations describing a single particle settling velocity, the equation proposed by Chien [50] is a unique relation to predict particle settling velocity. This formula involves the particle shape to fit the concept of sphericity. Based on the French units system, Chien's model for irregular particle settling was given as:

$$v_s^2 + 4.458\exp(5.03\varphi)\left(\frac{\mu_e}{d_p \rho_f}\right)v_s - 19.449\exp(5.03\varphi)d_p\left(\frac{\rho_p}{\rho_f} - 1\right) = 0 \tag{3-43}$$

In addition to the shape factor effect, this equation able to handle different rheological models, and could be applied for wide range of particle Reynolds number

(0.001-10,000). Moreover, this equation matches different properties of the fluids, according to their rheological characteristics, which clearly appear in the term of the effective viscosity. Therefore, the effective viscosity term can be selected according to the operated fluid properties.

Among the four familiar rheological models, the Bingham plastic, Herschel-Bulkley, Power-law and Casson, the most suitable rheological model to characterizes the drilling-mud behavior is the power-law model, at which it has ($n$<1). The use of Bingham Plastic and Casson models has proven their inability to model the behavior of drill-mud [46]. Therefore, the effective viscosity of the drill-mud will be represented by the formula:

$$\mu_e = K\left(\frac{v_s}{d_p}\right)^{n-1} \tag{3-44}$$

Particles drag coefficient and particle Reynolds number were extremely important when dealing with saltaion behavior. Since the viscous and inertia forces were the most effective forces during the settling, results of particle settling in this investigation were analyzed on the light of $Re_p$, which, $Re_p$ in non-Newtonian fluid is defined as following [4]:

$$\mathrm{Re}_p = \frac{0.1617\rho v_s^{2-n} d_p^n}{36^{n-1} K} \tag{3-45}$$

### 3.3.8 The Hindered Settling Velocity

There is no doubt that poor solid proceeding plant performance and erosion caused by the particle impacts could add a high cost to the execution of engineering applications. In addition, the economics of well drilling is greatly related to the cleaning process, which is also crucial to the industry. Hence, for the sake of precision, attention must be directed to the impact of particles once multi-phase flow is involved.

Interference between particles greatly affected their movement behavior. Therefore, clustering of cutting particles must consciously be accounted once deal with solid particle transport process. The particle hindered behavior defined as function of suspension concentration [4] which uses to interpret the influence of particle collision.

To simulate the transport of the solids, it is extremely important to take into account the existence of interference between the particles cluster during the settling. Richardson and Zaki 1954 [13], Thomas 1963 [4], and Ham and Homsy 1988 [64] studied the collision behavior of solid particles. By use of correlation factors, they have related the settling of solids cluster to a single particle settling velocity. Accordingly, a multiplication factor to account for the cuttings collision was involved in the present model.

The most two familiar correlation used in the field of the cuttings transport studies to used to evaluate the hindered settling were, Thomas, and Ham and Homsy. The former developed hindered settling velocity correlation as stoke's law correction using a multiplying factor, and attained to the expression shown in equation (3-46). The later emphasized that, the hydrodynamic dispersion of the suspended particles was an outcome of the viscous forces between the particles, and they presented their hindering velocity relation as given in equation (3-47). This correlation was valid for solids volume fractions $c_s$ in the range 2.5–10%.

Repeatable use of the correlation provided by Thomas was observed in some of the previous particles transport studies, such as in [3, 65], which is given by:

$$v_h = v_s e^{(-5.9 c_s)} \tag{3-46}$$

In the current model formulation it's meant to avoid this repetition where a more recent factor at [64] was used to hinder the drilled cuttings settling velocity, as given by the following:

$$v_h = v_s\left(1 - 4c_s + 8c_s^2\right) \tag{3-47}$$

Together, the above set of equations represent our proposed numerical model for a concentric, horizontal, annular and two-phase flow of power-law non-spherical cuttings, used to study transport during the wells cleaning process. Highlighting that the main seven equations in the system are **(3-4), (3-7), (3-18), (3-30), (3-34), (3-35) and (3-39)** targets to find seven unknowns. These seven unknowns are:

1. The velocity of the suspension layer $U_s$.
2. The velocity of the moving-bed layer $U_m$.
3. The cuttings concentration in the suspension layer $c_s$.
4. The cuttings concentration in the moving-bed layer $c_m$.
5. The thickness of the moving-bed layer $t_m$.
6. The dispersive shear stress between the moving-bed and stationary-bed layers $\tau_{mb}$.
7. The annulus pressure drop $dp/dz$.

Notice that the work is going to flow as per Figure 3-7

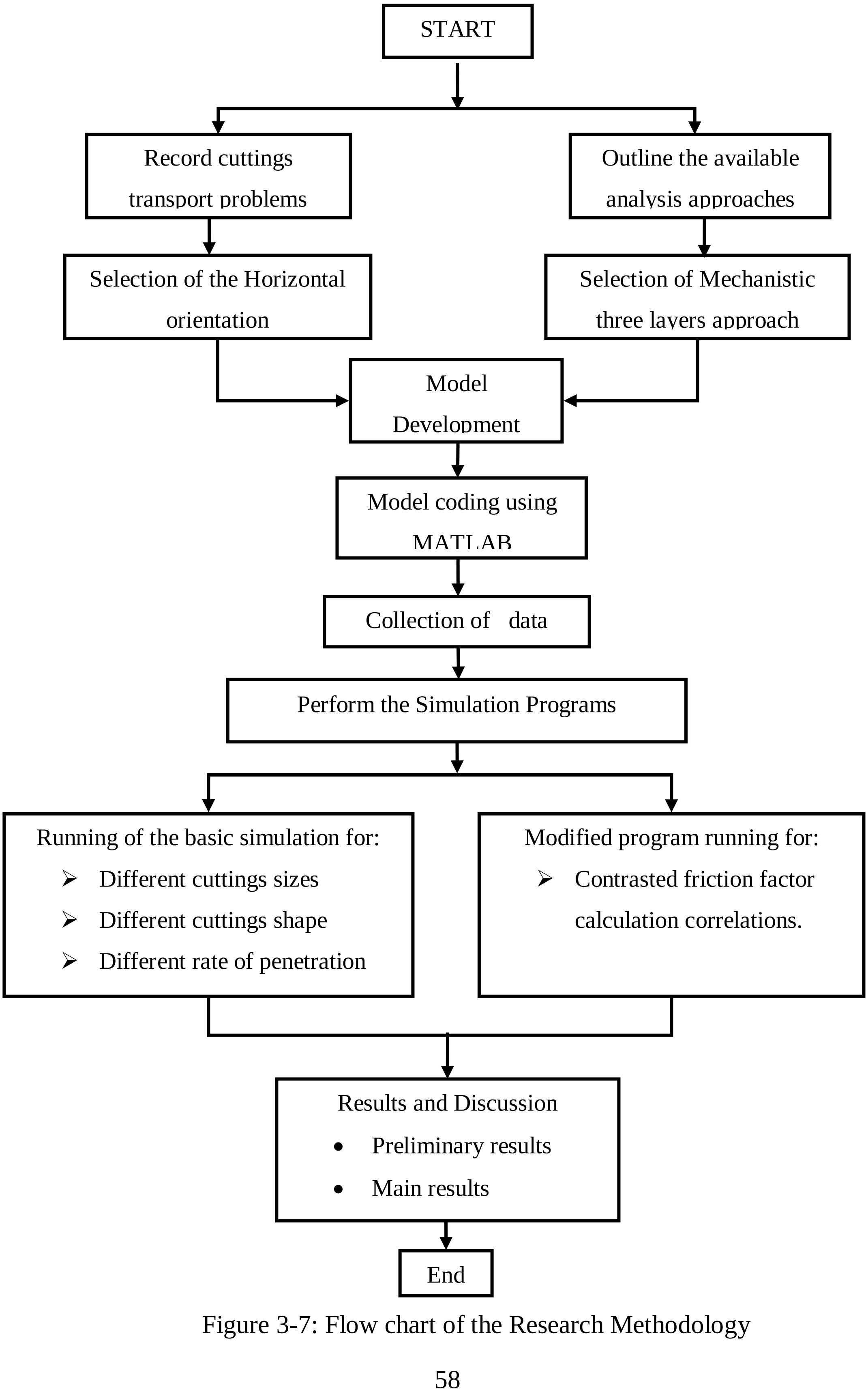


Figure 3-7: Flow chart of the Research Methodology

### 3.4 Models Solution Procedures

Generally, there are two strategies required to achieve a successive solution for a mathematical model. The first is to create perfect set of sequential steps for the system of equations, and the second is to define some required constraints in some steps to manage the system. In addition to the necessity of homogeneity between the two strategies, both strategies should properly fulfill the mathematical rules and agree with the physics of the transport phenomena.

However, the objective of this simulation was to evaluate the performance of the cutting transport under various operational and design conditions. Thus, the question may arise, "what are the indicators for good/bad transport performance" The answer is as follows:

For good transport performance:

- There must be a moving-layer to erode the stationary-bed and to attract the settled particles to move and transfer into the suspension layer.
- The height of the stationary-bed should be reduced, while the thickness of the suspension must increase.
- The concentration of the suspension must continually increase.

As well as the seven unknowns involved in the model, the seven equations should be available to be solved simultaneously. The developed non-linear system of equations needs to be solved numerically in order to predict some impressive parameters, and those could then be used to evaluate the performance of the model. To detect the mentioned indications, the model needed to first be able to predict the seven unknowns mentioned in the previous chapter.

Below is the illustration of the main features adopted to solve the developed model of horizontal cuttings transport:

### 3.4.1 The Operational and Design parameters

The research was carried out under various operational parameters and design parameters, as shown by the following:

a. The rheological characteristic as viscosity of the drill-mud have impeded in this work, as formulated in the power law of non-Newtonian fluid, which is specified by the value of index behavior *n* and consistency index *K* given in Table 3-1.

Table 3-1: The adopted viscosities of the drill-mud

| **Source** | **Class of Power-Law Viscosity** | **Fluid Viscosity / power-law** | |
|---|---|---|---|
| | | **K** $lb_f.s^n/ft^2$ | **n** |
| [4] | Low viscosity | 0.00600 | 0.68 |
| [19] | Low viscosity | 0.00084 | 0.68 |
| | Intermediate viscosity | 0.00436 | 0.61 |
| | High viscosity | 0.00930 | 0.61 |

b. The fluid density given in French units to investigate the particles behavior given in Table 3-2

Table 3-2: Density of drill mud

| **Source** | **Fluid Density g/cm$^3$** |
|---|---|
| [18] | 0.9982 |
| | 1.1983 |
| | 1.4379 |
| [4] | 1.1024 |

c. The shape factor, which represented by the sphericity, was investigated within the range 0.75-1. Few studies were found to be concerned about the size and shape of the cutting, such as in [4, 42, 53]. In this research, special consideration was given to the probable shape and the resultant sizes of the drilled cuttings. This was done in order to more accurately analyze the contribution of these factors in transport performance.

d. The widely measured cuttings size in the drilling process is adopted in this work as in Table 3-3.

Table 3-3: The provided cuttings mean diameters (cuttings size)

| **Source** | **Size** | **Particle Diameter** |
|---|---|---|
| [19] | large | 0.25 in |
| [29] | medium | 0.175 in |
| [66] | small | 0.03 in (0.76 mm) |

e. The particle density to inspect the particles behaviors in French units will be as following Table 3-4:

Table 3-4: The tested particle densities

| **Source** | **Particle Type** | **Particle Density g/cm$^3$** |
|---|---|---|
| [66] | Carbolite | 2.71 |
| | Bauxite | 3.56 |
| | Light weight prppant1 | 1.25 |
| | Light weight prppant2 | 1.75 |

f. The annular size as per common practices of wells drilling is given below in Table 3-5.

Table 3-5: The annular sizes studied in the simulation

| **Source** | $D_w$ (in) | $D_p$ (in) |
|---|---|---|
| [39] | 8.75 | 4.50 |
| [29] | 8.00 | 4.50 |
| [4] | 5.00 | 1.90 |
| - | 5.00 | 2.375 |

g. The Rate of Penetration or, (ROP) values were selected as in Table 3-6.

Table 3-6: The selected value of operational ROP

| **Source** | **ROP** (ft/hr) |
|---|---|
| [4] | 50 |
| [23] | 60 |
| [29] | 30 |
| [42] | 15 |

Highlighting that in the basic and modified models the particle and the fluid density are fixed at 163.60 $lb_m/ft^3$ or (2.62 $g/cm^3$), and 68.82 $lb_m/ft^3$ or (9.2 lb/gal) respectively. Drilled-cuttings removal occurs at high annular velocity rather than low velocity. Incremental annular velocity might be applied to achieve wellbore cleaning.

### 3.4.2 Calculation of the Well Geometry

As a result of the gradual increase in the mud annular velocity, the layers heights and other dependant geometrical quantities will automatically change. At the same time, a cross section of the annular geometry combined with existence of three diverse layers during the flow will result in more complex calculations than those of the simple pipe flow geometry.

Brown et al. [21] reported that pipe eccentricity reduces the cleaning rate per unit of time while the pressure drop is small compared to a centralized pipe. Kamp and Rivero [39] observed that increasing the eccentricity increases the bed height. Zamora et al. [67] showed that a fully eccentric annulus resulted in highly skewed flow. As a consequence, the annular configuration in this research was held as a concentric annulus. The choice of a drill-pipe rather than straight tubing was based on the findings of Zhou and Shah [68], who demonstrated that the pressure losses in coiled tubing were significantly higher than with straight tubing.

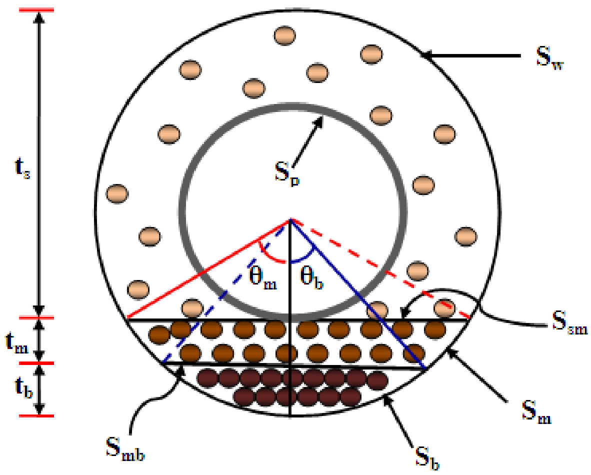


Figure 3-8: The Three layers angular thicknesses, highest and witted perimeters

As shown in Figure 3-8, several geometrical terms must be pre-calculated. These terms clearly appear in various equations of the developed model. Layers heights, areas, perimeters and hydraulics diameters are important quantities in the set-up of the main equations in this simulation system. The layers area required to be inserted into the continuity and momentum equations. The hydraulic diameters (based on the perimeters) are necessary in the estimation of Reynolds number. The moving-bed height is involved in the calculation of the dispersive shear. The suspension-layer height must be use to approximate the suspension concentration. All of these are critical quantities which greatly depend upon the geometry calculations.

Therefore, the well known trigonometric functions and areas of the plane shapes were engaged to create a geometrical calculator. This is according to the possible cases showed in Figure 3-9. The special program was written to generate the required calculations, and attached to the main program as sub-routine. The derived geometrical formulas are called the **geometry engine** (Appendix A)

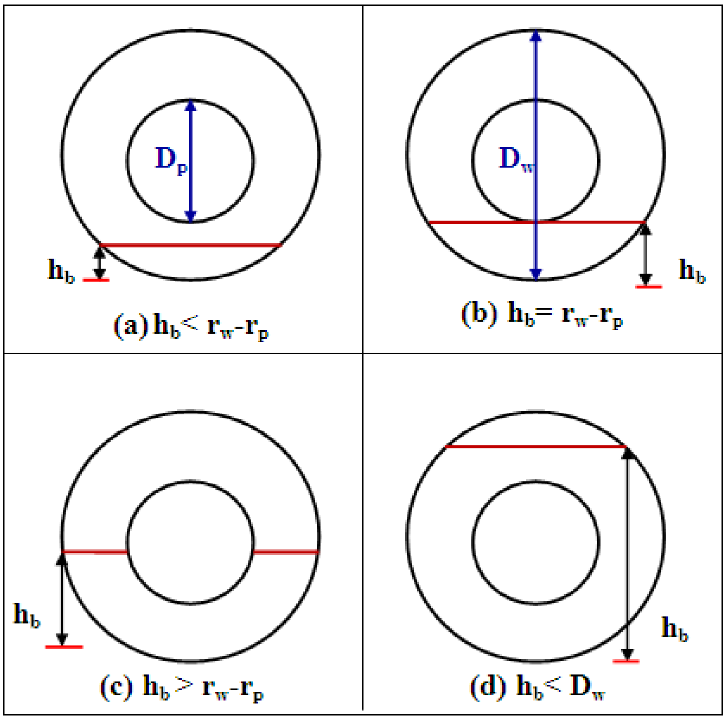


Figure 3-9: Different cases for the formed bed heights

### 3.4.3 Algorithm Development

An algorithm is a description of how a sequence of the established instructions will be executed to achieve the simulation tasks. The MATLAB R2008a software was used in this research to write the sequence of tasks which represented the simulation code.

The development algorithm is crucial to the understanding of the vital parameters, the equations, and the physics of the annular transport phenomena. The main challenge in this research was assessing a possible perfect solution matching with the logical mathematics and physics of the phenomena for the complicated non-linear developed system. Thus, intense efforts and a considerable amount of time have been spent in this section. To facilitate the solution, the following requirements were adopted:

*3.4.3.1 Assumptions*

In addition to the hypotheses presented in chapter 4, several other explicit assumptions were proposed in order to solve the developed model.

Since both of the two popular relations used to investigate the particles settling and hindered behaviors were stand on suspension concentration, performing of this investigation demanded to assume that total cuttings concentration in the annulus given by equation (3-6) was fully suspended. According to this equation, the particle hinder behavior must be affected by the operational ROP and the applied annular fluid velocity.

Assuming the validity of the effort by Zou et al. [34], the build-up of the bed inside the annulus can be predicted. It was assumed that the cuttings bed was already observed, and the cuttings bed removal occurred at level of bed height below the drill-pipe.

Since the worst case condition occurred when the stationary-bed touched the drill-pipe, the expectation of pipe wear and erosion causes must be taken into account. Accordingly, the case in which the stationary-bed is larger than ($r_w$-$r_p$) will not be considered in this analysis. It was proposed that the height of the bed was less than the drill-pipe level by the amount of a single particle diameter (large). This fulfils the consideration for the worst case condition. Thus, existence of such a case would create barriers to transport and threats the occupations of drilling instruments and tools performance that consequently lead to the blockage of wellbore

One of the important assumptions was that the studied annular section is relatively far from the drill face, which based on study by Gavignet and Sobey [40].

Another assumption made was to suppose that the bottom bed layer was completely stilled, this building a dead-layer. Hence, the velocity of the stationary-bed layer was approximated to be zero ($U_b = 0$) [42]. Note that, behavior of the flow near to the bed may tend to be slower, that could return alternatively laminar flow patterns.

*3.4.3.2 Iteration procedure*

As clearly visible, the model is a complex non-linear system, which required a huge application of iterative procedures at many parts of the system to achieve solution for the seven previously mentioned unknowns. Newton's methods for non-linear equations were employed in wide range to obtain solutions for some of the involved variables. In order to solve Chien's equation (3-43) for cutting settling velocity, the well known Newton-Raphson method has been used. The solution algorithm to solve and hinder the particle settling velocity is shown in Figure 3-10.

The Bisection method was used to solve the non-linear Szilas equation (3-13), in order to achieve an effective solution for the friction factors in the guess ranges between (0-1).

Particular iterative procedures to calculate $U_s$, $c_s$, $U_m$, and $t_m$ based upon deep understanding of the physics of the phenomena and the equations were applied in order to obtain a satisfactory solution for the complicated horizontal cuttings transport model.

*3.4.3.3 Constrains*

Because of the broad applicable values for the annular velocity and different parameters during the iteration, the manual follow-up of the solution is not a practical issue. Therefore, some constraints must be invoked in order to binding the limits of the solutions. Nevertheless, the program run-stop criterion must also be constructed to terminate the running of the program and enable results printing.

The loops and statement facilities in MATLAB was greatly employed to enforce the stated constraints. These constraints were accomplished by initiation of acceptable logical conditions at specific optimal reference points providing them in terms of specific errors or accuracies. The sequence of the simulation algorithm is illustrated in Figure 3-11.

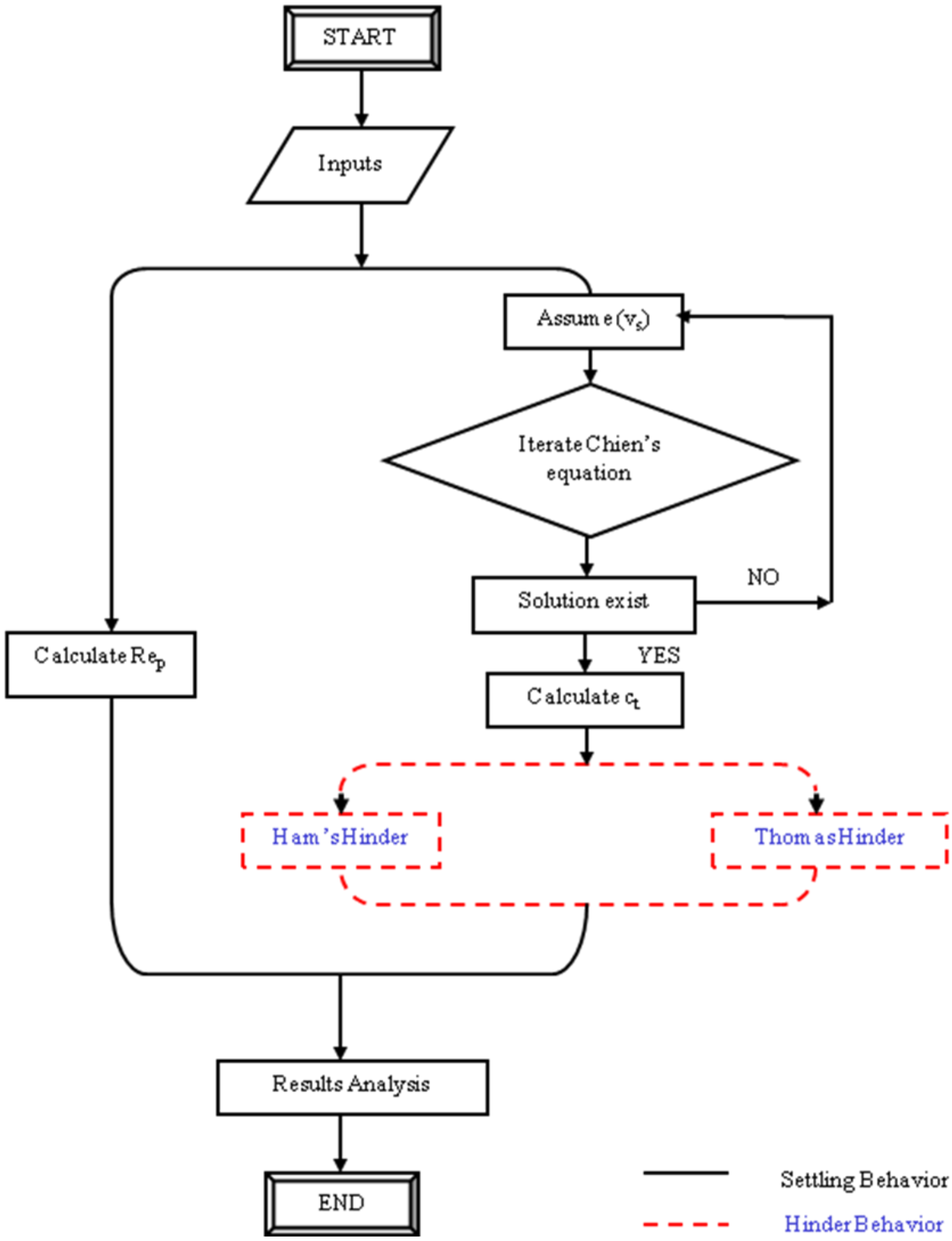


Figure 3-10: Hierarchy Chart to solve and hinder the particle settling

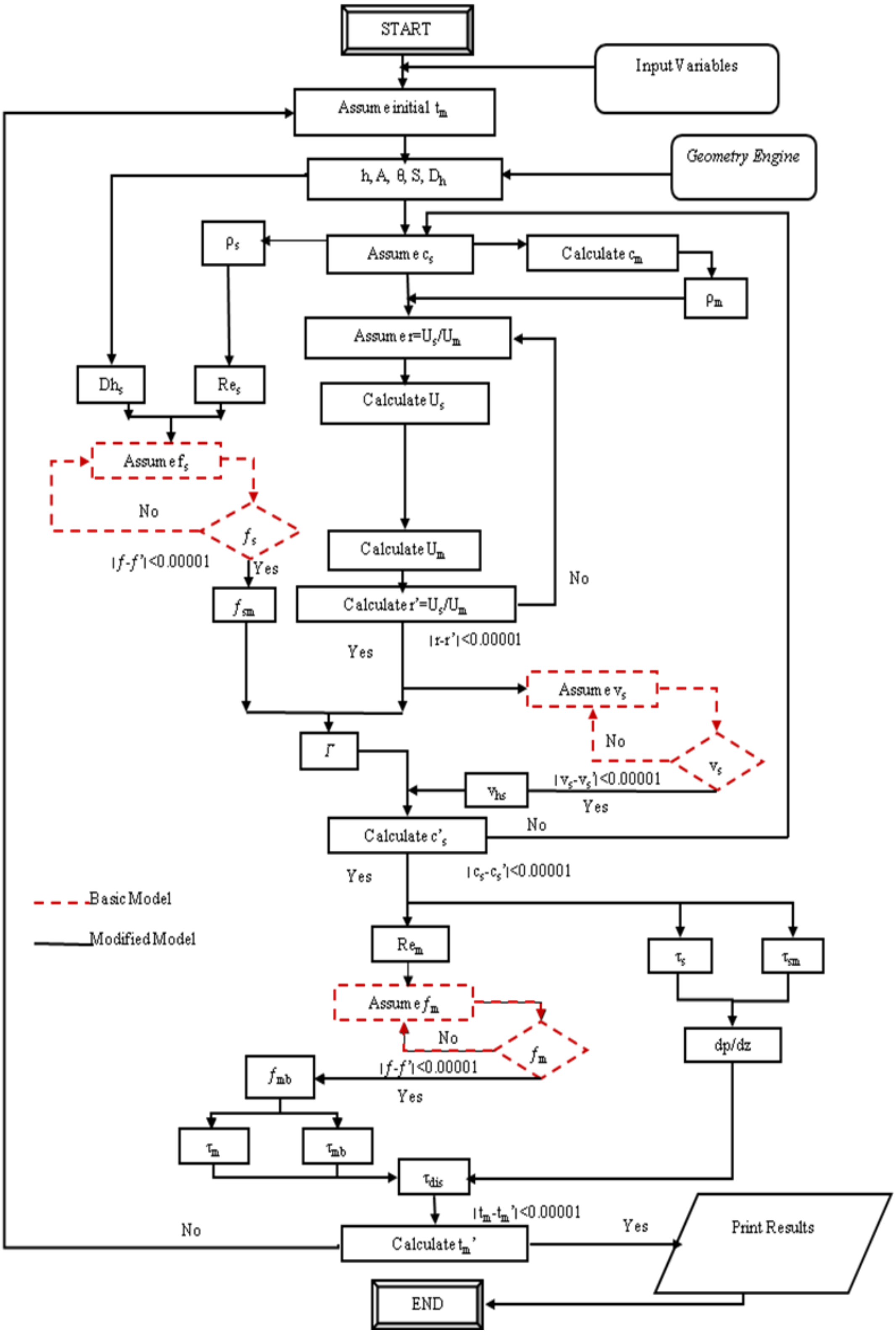


Figure 3-11: Hierarchy Chart to solve the developed models.

### 3.5 Sequence of Model Solution

Below are the sequenced, step-by-step procedures followed to solve the models in the MATLAB program:

**Step # 1)** Set the annular velocity to the value of 0.75 ft/s to solve the first simulation. After this, the same step will be repeated with an increase in the annular velocity beginning with a value of 0.75 ft/s and rising to the last available velocity in order to reach full bed cleaning by solving from step 1 to step 26.

**Step # 2)** Assume an initial small moving-bed layer thickness ($0 < t_m < 0.00001$).

**Step # 3)** Calculate the layers dimensions and related inputs using the created geometry engine to calculate layers heights, layers areas, layers angels, layers perimeters and layers hydraulic diameters.

**Step # 4)** Calculate total concentrations of the drilled cuttings using the relation given in equation **(3-6).**

**Step # 5)** Assume low concentration value for cuttings concentration in the suspension layer.

**Step # 6)** Calculate cuttings concentration of the moving-bed layer according to the linear concentration distribution given by the relation in equation **(3-33).**

**Step # 7)** According to the assumed concentration the effective densities of the layers will be calculated using the equations **(3-10), (3-23)** and **(3-29).**

**Step # 8)** Assume the ratio $\boldsymbol{r}$ of the mean suspension layer velocity to the mean velocity in moving-bed layer ($r=U_s/U_m$).

**Step # 9)** Solve the continuity equation to calculate the mean suspension layer velocity, using equation **(3-4).**

**Step # 10)** Calculate the generalized Reynolds number. of suspension **(3-11)** based upon the suspended layer mean velocity and effective density.

**Step # 11)** Import the hydraulic diameter of the suspension from the Geometry engine and iterate Szilas equation **(3-13)** to calculate the friction factor between the upper suspension layer and walls of the well, and pipe up to accuracy $|f\text{-}f'|<0.00001$.

**Step # 12)** Calculate the interfacial friction factor between suspension and moving bed layers according to **(3-15).**

**Step # 13)** Calculate the mean velocity of the Moving-bed layer using equation **(3-34)**

**Step # 14)** Calculate the new ratio *r'* between the obtained suspension and moving bed mean velocities to check the error of the assumption in **Step # 8** up to accuracy of $|r\text{-}r'|<0.00001$.

**Step # 15)** Using the mean layers velocities and interfacial friction factor, calculate the cutting particles diffusivity coefficient equation **(3-41).**

**Step # 16)** Iterate Chein's settling velocity equation **(3-43)** to obtain the particle settling velocity.

**Step # 17)** Hinder the particle settling velocity using the suspension concentration by Hams and Homey's correlation **(3-47).**

**Step # 18)** Calculate the suspension layer concentration using the convection-diffusion equation. Check the error of suspension concentration assumption in **Step # 5** up to accuracy of $|c_s\text{-}c_s'|<0.00001$, and thereby the following calculations would be amended.

**Step # 19)** Calculate generalized *Re* no. in the moving bed layer using the layer effective density and mean velocity.

**Step # 20)** Iterate Szilas's equation to calculate the friction factor between the moving bed layer and the well wall.

**Step # 21)** Obtain the interfacial friction between the moving and stationary-bed using the concept at (**3-21**)**.**

**Step # 22)** Calculate all exerted shear stresses according to the layers movement using the set of equations **(3-8), (3-9), (3-19), and (3-20).**

**Step # 23)** Calculate the pressure drop using the upper layer momentum equation **(4.9).**

**Step # 24)** Utilize the relation between equation **(3-25)** and **(3-30) in (3-18)** to calculate the dispersive shear stress.

**Step # 25)** Calculate the moving-bed thickness from its relation with the dispersive shear stress given by equation **(3-30).** Check the moving bed thickness assumption in **Step # 2** up to accuracy of $|t_m - t_m'| < 0.00001$

**Step # 26)** Print the results of the seven unknowns, the important parameters, and then end the program.

Note that, the above **26 steps** were followed to obtain the values of the seven required unknowns at bed height and each given annular velocity.

Without further alter on the previous theoretical steps, an additional solution beyond the first set was obtained by making changes to some of the model equations. Mainly, Szilas' correlation in **(3-13)** was replaced by the other frictional factor empirical relations, which is given by **(3-16)** and **(3-17),** that enabled opportunity of diverse model simulation.

### 3.6 Summary

In this current chapter, all aspects of the equations required to initiate simulation of the cutting particles transport in horizontal annular conduit have been specified. The chapter reviewed the main features of the developed three layered model. The importance of some equations needed for the installation of the model, such as convection-diffusion, settling velocity and hinder settling velocity factor were highlighted.

Moreover, extra equations beyond the model requirement were added to this section for the purpose of generating an alternative method to calculate the friction factors and to examine its effect. Thus, preparation of modified model will permit a contrasted program to be run, and thereby comprehensive comparisons could be conducted.

The chapter denotes the referenced input data, and presented the details of the developed system solution procedures. Beside justifications of selection of the fluid and particle features, several essential assumptions were justified. In addition, some of the constraints necessary to proceed with the simulation and to activate the model were presented. The scenario of the model solution in a step-by-step manner was also specified.

With incremental increase in the annular velocity, identical steps were similarly followed to simulate the process of cleaning for the modified model, except that in the modified case there was no need to apply the Bisection method.

# Chapter 4

# Results and Discussion

## 4.1 Introduction

This chapter presenting analysis of the results obtained from the developed models. As well known, particle settling behavior plays a major role in the formation of cuttings bed layer. Accordingly this chapter document two important phenomena, first, is the settling behavior of single non spherical particle falls in non Newtonian fluid, and second is the hinder behavior cased by collision of solid particles. Besides, the influence of the sphericity factor $\varphi$ in the behaviors was involved. In advance the chapter also presented the results obtained from the developed model where the cuttings transportation process was investigated into two different evaluation procedures for the frictional shear forces. Hence, the models results are presented into two subsections. The first subsection present and discuss performance of the cuttings transport by evaluating the frictional shear stresses according to Szilas hypothesis, which consequently will be called the basic model results. The second subsection present and discuss performance of the cuttings transportation using other empirical correlations captured from the literature to evaluate the frictional shear stresses, and this will be called the modified model results.

## 4.2 Particle Settling Behaviour

The behavior of particles settling is very important in various multi phase flow applications. In petroleum applications, slurry flow of drill-mud with the drilled cuttings in transport process is an important application. As shown in Figure 4-1, transport of single cutting particle strongly influenced by the flow direction. Hence, the settling behavior represents important tangible phenomena especially in the directional drilling. Indeed that deeper understanding of this phenomenon is crucial to model and analyze the targeted performance in drilling process. The required minimum velocity to transport solids depends upon the amount and behavior of settled particles.

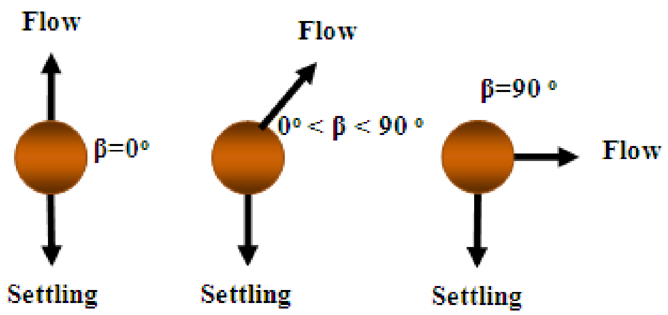


Figure 4-1: Particle settling in vertical, inclined and horizontal flow

### 4.2.1 Results and Discussion of the Settling Behaviour

Investigation of the settling behaviour was carried through different particles characteristics and different fluid properties and the results showed the following:

#### *4.2.1.1 Effect of Particle Density on Particle Settling*

To vary the particle density, an 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 Figure 4-2 (a). 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 1.25 g/cm$^3$, the contribution of the shape factor on settling velocity was small. Thus, settling velocity of low particle density 1.25 g/cm$^3$ of shape factor range 0.75-0.9 was changed in a range of 2.22 and 2.34 cm/s. The settling velocity of the high particle density for the same sphericity range is observed to range between 30.82-42.95 cm/s.

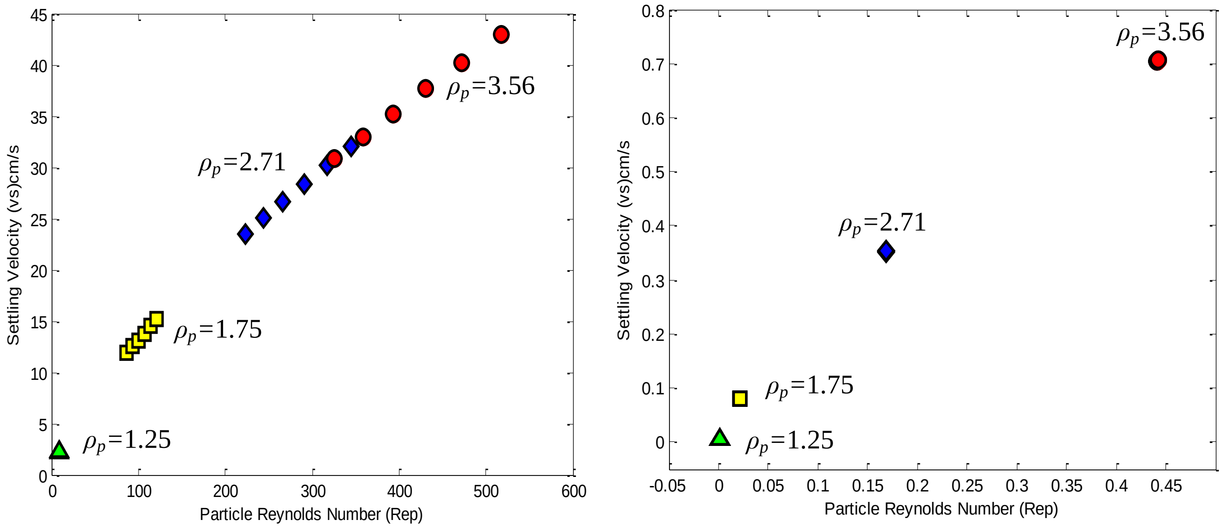


Figure 4-2: Effect of particle density on settling velocity of (a) large particle sizes, (b) small particle size

As shown in Figure 4-2 (b), flow of small particle size of 0.08 cm diameter with different particle density was lower. Highest particle density of 3.56 g/cm$^3$ was settled down at 0.7 m/s 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. [69], agreed that due to the gravitational effect greater particle density is harder to be lift.

#### *4.2.1.2 Effect of Particle Size on Particle Settling*

To examine the particle size effect, the settling behavior was encountered at intermediate fluid viscosity *K*=0.2088 Pa.sn, *n*=0.61. Figure 4-3 (a) 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 Figure 4-3 (b). 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 0.70 cm and 0.9 shape factor was reduced from 17.98 to 6.44 cm/s.

Moreover, flow of small size particle of 0.08 cm at low fluid density was low. Small size has lower settling velocity even at high sphericity factor 0.9 compared to the large sized particles which has a significant settling velocity of 17.98 cm/s.

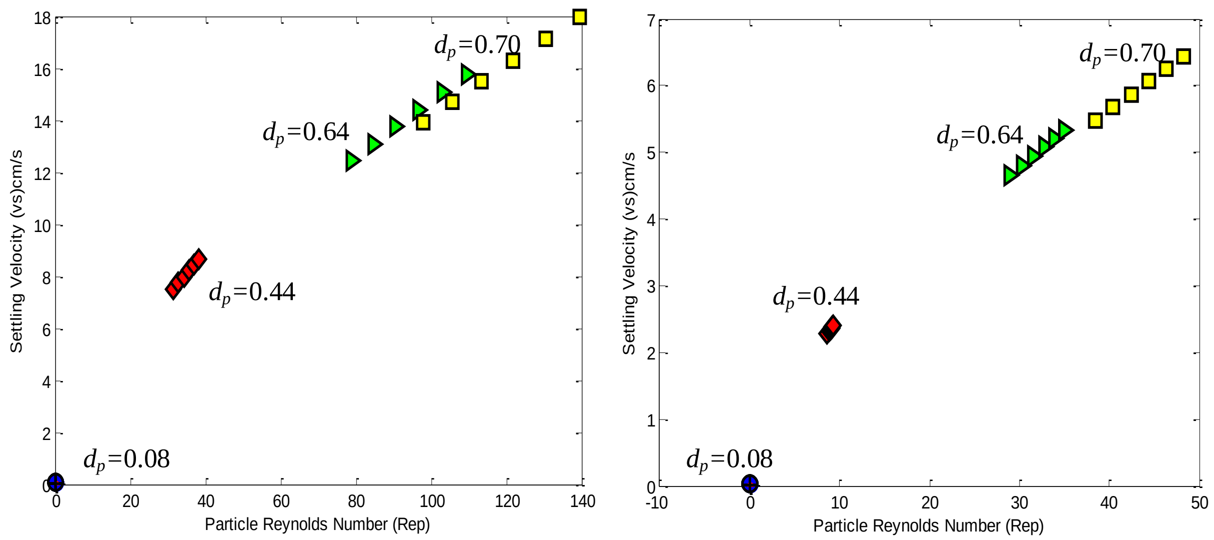


Figure 4-3: Effect of particle size on settling at (a) low fluid density, (b) high fluid density.

Large sized cuttings found to behave more settling, Zhou [37], observed that larger cuttings cleaning are the most difficult. On the other hand Ozbayoglu et al. [69] , 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.

*4.2.1.3 Effect of Fluid Density on Particle Settling*

To inspect the effect of fluid density, medium particle size of 0.44 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, Figure 4-4 (a) 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 particle sphericity was found to settle at 6.84 cm/s. While at low fluid density of 0.9982 g/cm$^3$, similar particle exerted 14.18 cm/s settling velocity.

In Figure 4-4 (b) 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.

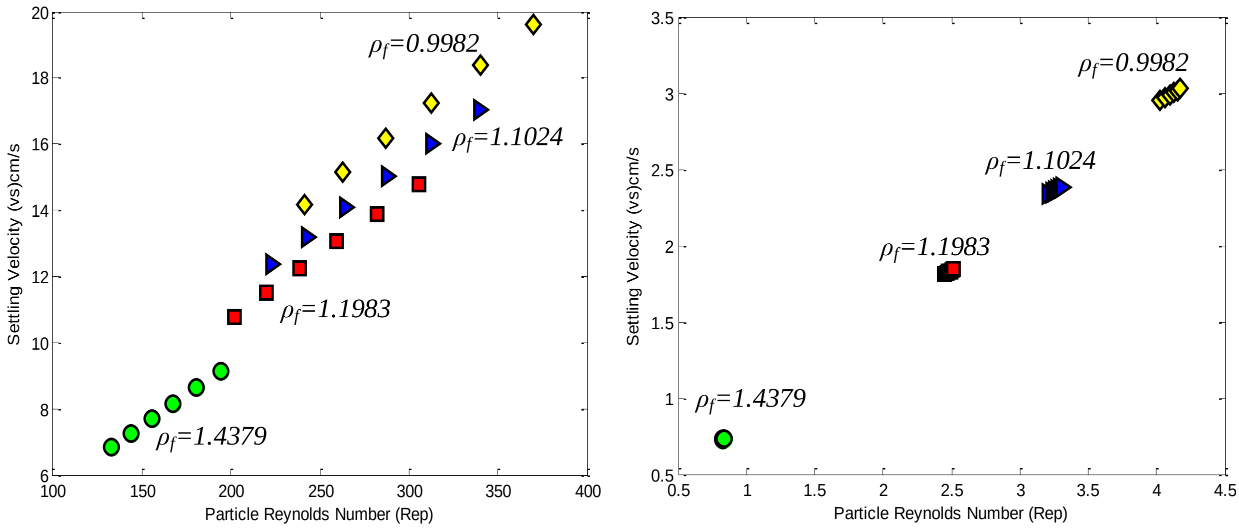


Figure 4-4: Effect of particle density on settling at (a) low fluid density, and (b) high fluid density

This agrees with Zhou [37], 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. [69] reported that increase of the fluid density allows improving the bouncy effect as low force would be required to perform on the settled cuttings.

*4.2.1.4 Effect of Fluid Viscosity on Particle Settling*

Figure 4-5 (a) shows the effect of the viscosity on the settling. Settling of a small particle at different levels of fluid viscosity was low. Generally the settling behavior increased with decreasing of the fluid viscosity.

Larger regular particles of 0.70 cm fall faster in the lower fluid viscosity *K*=0.0402 Pa.s$^n$, *n*=0.68, as shown in Figure 4-5 (b). In instance, for large particle with sphericity 0.75, the minimum observed settling velocity was 5.22 cm/s which occurred at the lowest fluid viscosity. For large particle, the minimum velocity at sphericity of 0.75, was 14.85 cm/s, and the maximum velocity was 20.97 cm/s 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.

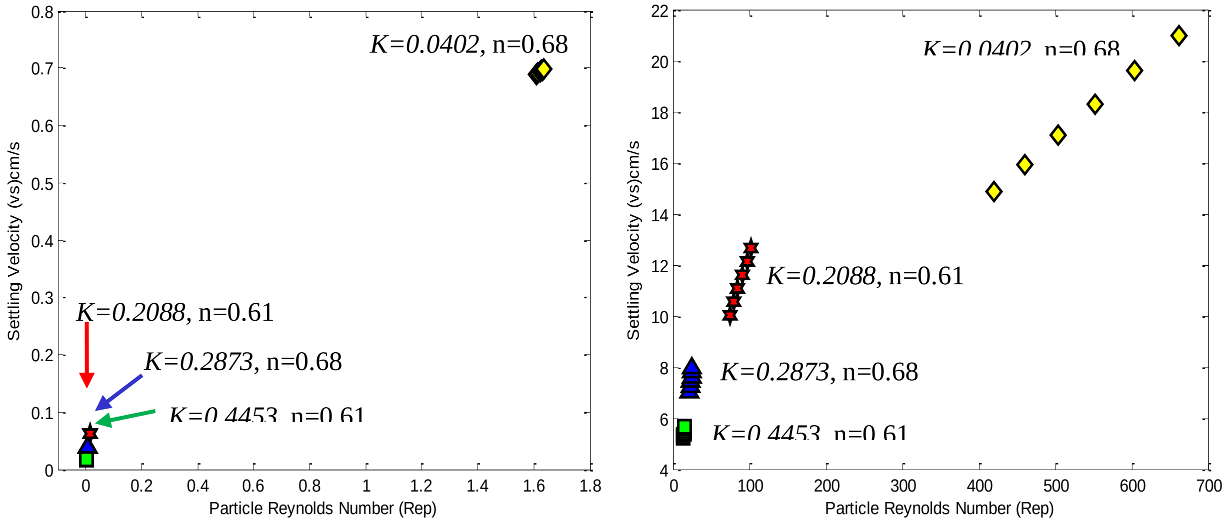


Figure 4-5: Effect of the fluid viscosity on settling behavior of (a) small particle size, and (b) large sized particle.

Increase in *K* value from 0.2088 to 0.4453 Pa.s$^n$ reduces the settling velocity for large particle 0.70 cm diameter at maximum sphericity 0.9 from 12.65 cm/s to 5.65 cm/s. 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/s to 7.96 cm/s and also reduced $Re_p$.

Thus, particle exerts high $Re_p$ at maximum settling velocity. Generally, slight increasing of the fluid viscosity helped to suspend the particle.

Ozbayoglu [69] 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. resists settling behavior. Besides, Adari et al [31], stated that removal of settled cuttings on bed enhance as $n/K$ ratio increases notice that their mentioned recommendation was made to meet highly inclined to horizontal flow direction.

### 4.3 Hindered Settling Behaviour

As much as particle settling velocity became higher, it will have more influence on the transport process. The previous investigation on the particle settling behavior indicated that, the high settling velocities occur at:

- Low fluid viscosities
- Low fluid densities
- High particle size
- High particle density

Therefore, the four condition were adopted in order to inspect the hinder behavior on the cuttings settling velocity using the two correlations in (3-46) and (3-47).

#### 4.3.1 Results and Discussions of the Hindered Settling Behaviour

According to adoption of the four situations, different cases of settling velocities were stated to encounter the hinder behavior through them. To generalize the outcome of the results, this inspection was made at high and low ROP 50 and 15 ft/hr, and performed for two annular velocities 2 ft/s as low velocity, and high velocity of 5 ft/s.

Using input data giving in chapter 5, the cases studied were divided into four groups as shown in Tables 4-1, 4-2, 4-3 and 4-4.

Table 4-1: prepared conditions to examine the particle hinder behavior case A

| **Case** | **ROP (ft/hr)** | **$U_a$ ft/s** | | **Fluid Viscosity** | | **Fluid Density ($g/cm^3$)** | **Particle Density ($g/cm^3$)** | **Particle Size (cm)** |
|---|---|---|---|---|---|---|---|---|
| | | Low | High | $K$ ($Pa.s^n$) | $n$ | | | |
| A | 15 | 2 | 5 | 0.2873 | 0.68 | 0.9982 | 3.56 | 0.70 |
| | 50 | 2 | 5 | 0.2873 | 0.68 | 0.9982 | 3.56 | 0.70 |

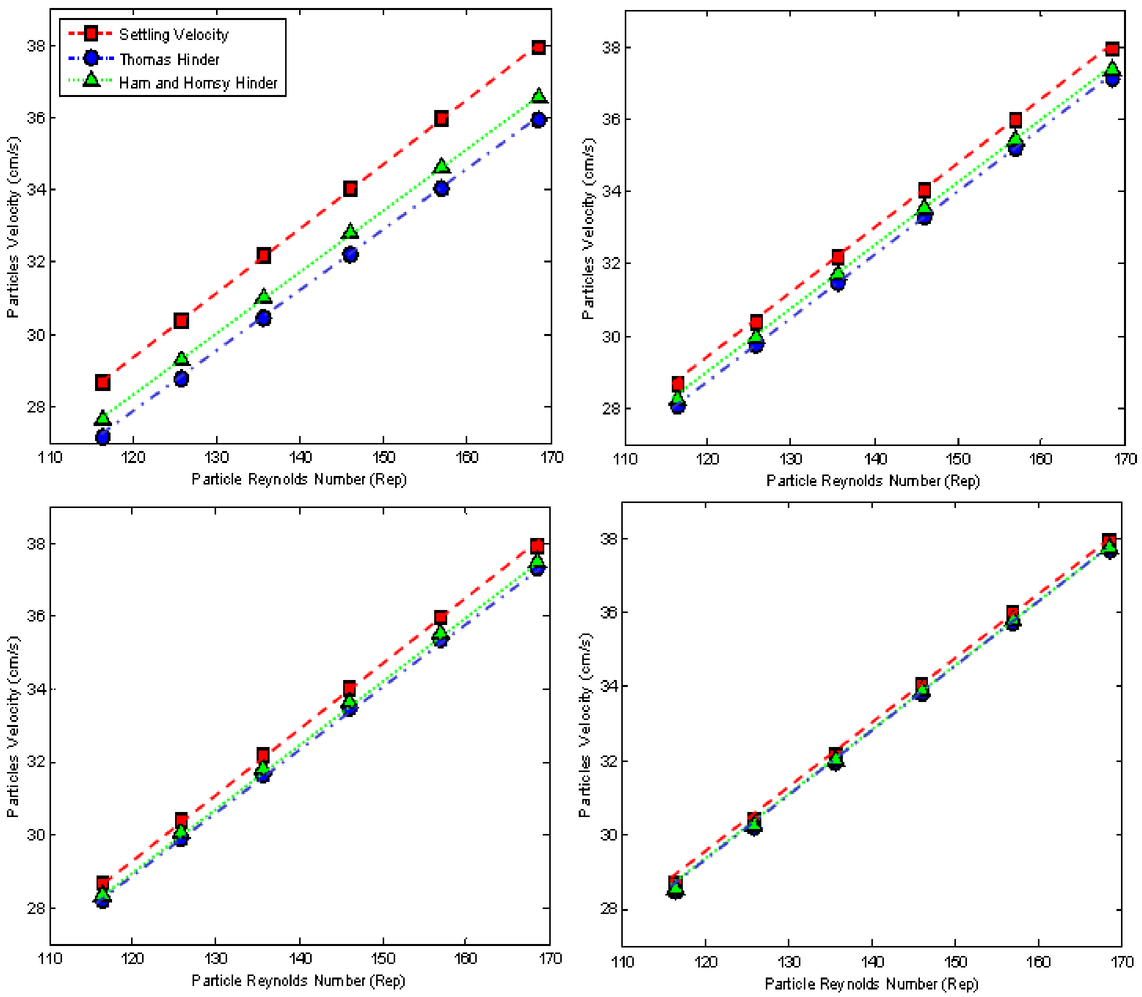


Figure 4-6: Case A, particles hindered settling velocity at (1) ROP/Ua=0.0069, (2) ROP/Ua=0.0028, (3) ROP/Ua=0.0021, (4) ROP/Ua=0.0008.

Table 4-2: Prepared conditions to examine the particle hinder behavior case B

| **Case** | **ROP (ft/hr)** | **$U_a$ ft/s** | | **Fluid Viscosity** | | **Fluid Density ($g/cm^3$)** | **Particle Density ($g/cm^3$)** | **Particle Size (cm)** |
|---|---|---|---|---|---|---|---|---|
| | | Low | High | $K$ ($Pa.s^n$) | $n$ | | | |
| B | 15 | 2 | 5 | 0.0402 | 0.68 | 1.1024 | 2.71 | 0.64 |
| | 50 | 2 | 5 | 0.0402 | 0.68 | 1.1024 | 2.71 | 0.64 |

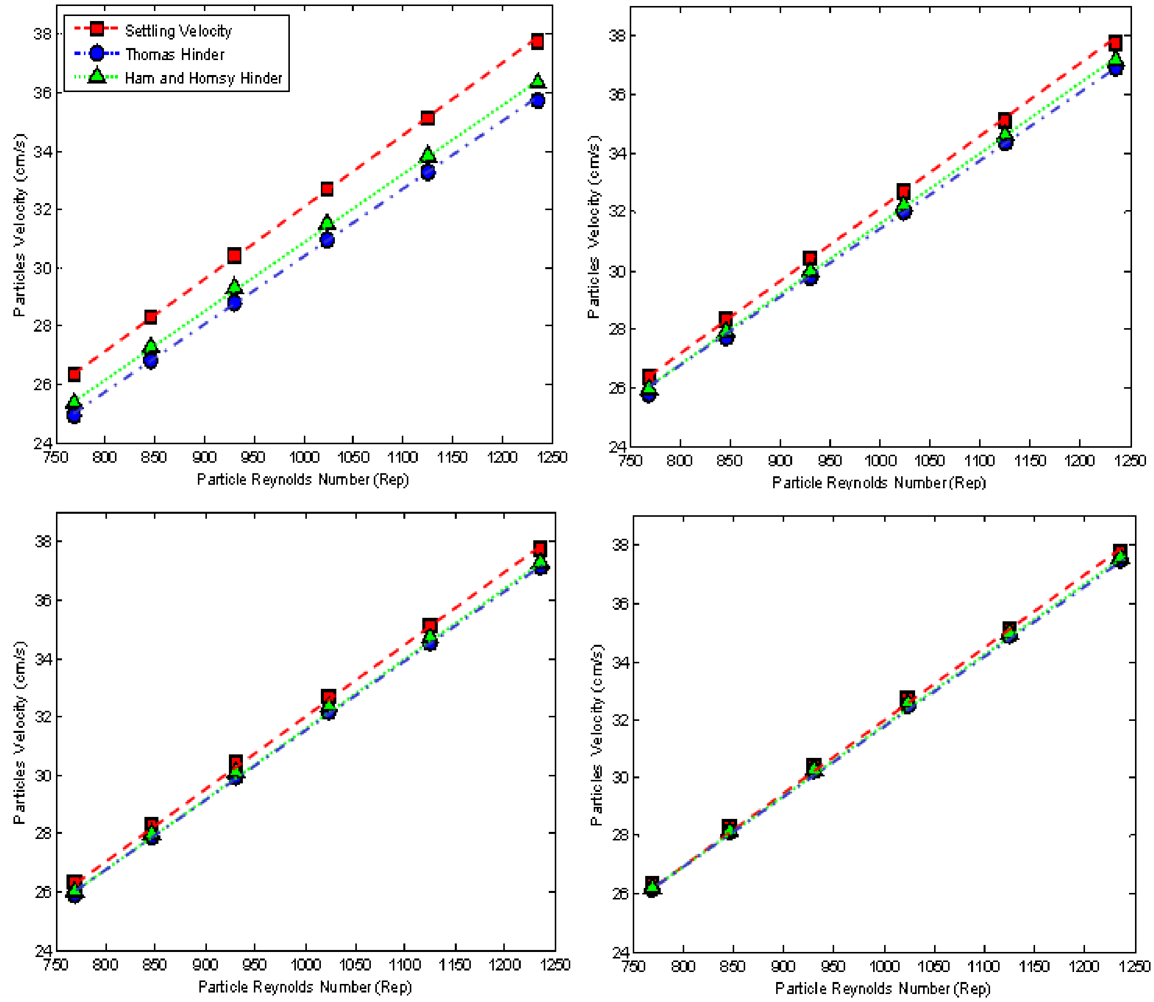


Figure 4-7: Case B, particles hindered settling velocity at (1) ROP/Ua=0.0069, (2) ROP/Ua=0.0028, ROP/Ua=0.0021 (3), (4) ROP/Ua=0.0008.

Table 4-3: Prepared conditions to examine the particle hinder behavior case C

| **Case** | **ROP (ft/hr)** | **$U_a$ ft/s** | | **Fluid Viscosity** | | **Fluid Density ($g/cm^3$)** | **Particle Density ($g/cm^3$)** | **Particle Size (cm)** |
|---|---|---|---|---|---|---|---|---|
| | | Low | High | *K* ($Pa.s^n$) | *n* | | | |
| C | 15 | 2 | 5 | 0.0402 | 0.68 | 0.9982 | 3.56 | 0.44 |
| | 50 | 2 | 5 | 0.0402 | 0.68 | 0.9982 | 3.56 | 0.44 |

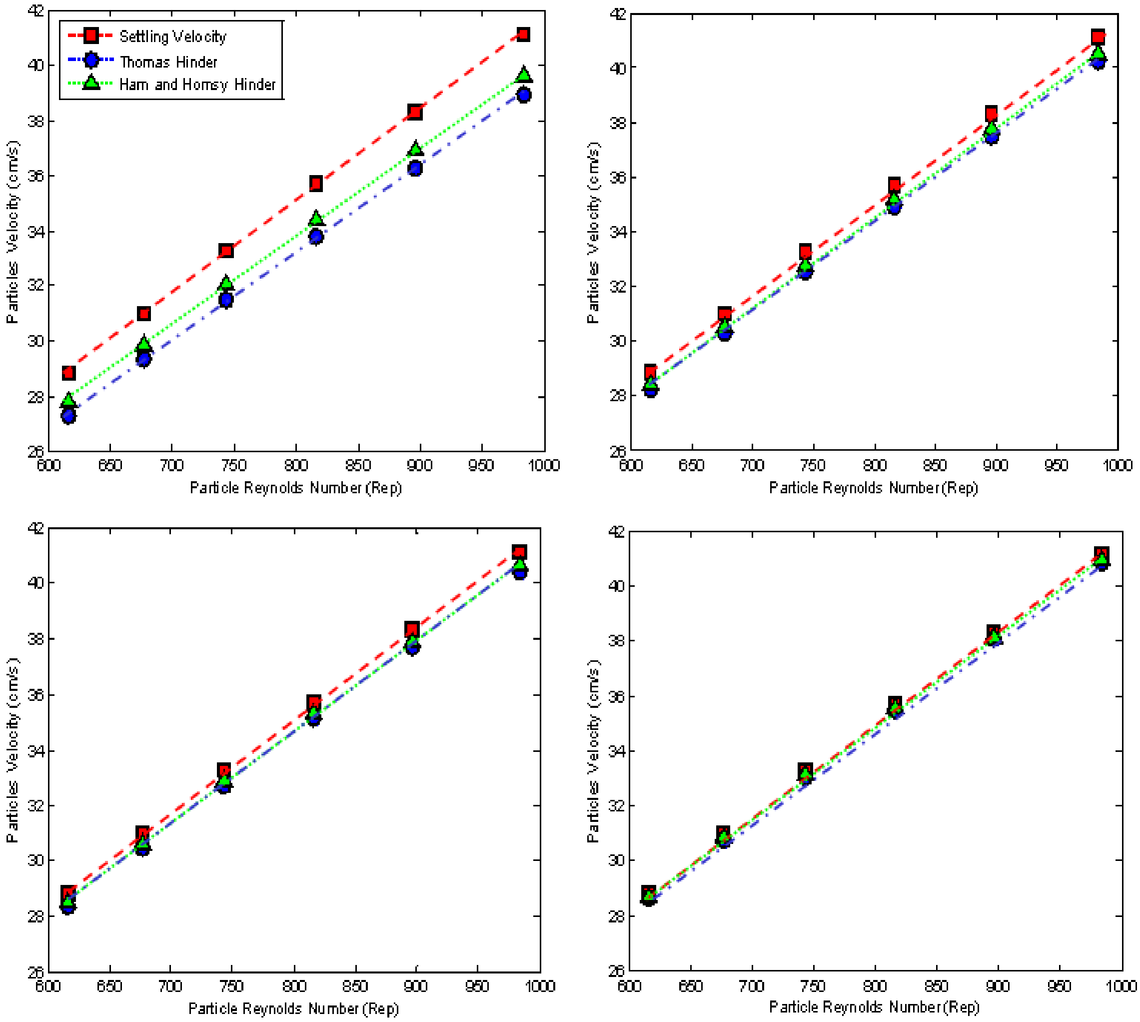


Figure 4-8: Case C, particles hindered settling velocity at (1) ROP/Ua=0.0069, (2) ROP/Ua=0.0028, ROP/Ua=0.0021 (3), (4) ROP/Ua=0.0008.

Table 4-4: Prepared conditions to examine the particle hinder behavior case D

| **Case** | **ROP (ft/hr)** | **$U_a$ ft/s** | | **Fluid Viscosity** | | **Fluid Density ($g/cm^3$)** | **Particle Density ($g/cm^3$)** | **Particle Size (cm)** |
|---|---|---|---|---|---|---|---|---|
| | | Low | High | $K$ ($Pa.s^n$) | $n$ | | | |
| D | 15 | 2 | 5 | 0.2873 | 0.68 | 1.1024 | 2.71 | 0.64 |
| | 50 | 2 | 5 | 0.2873 | 0.68 | 1.1024 | 2.71 | 0.64 |

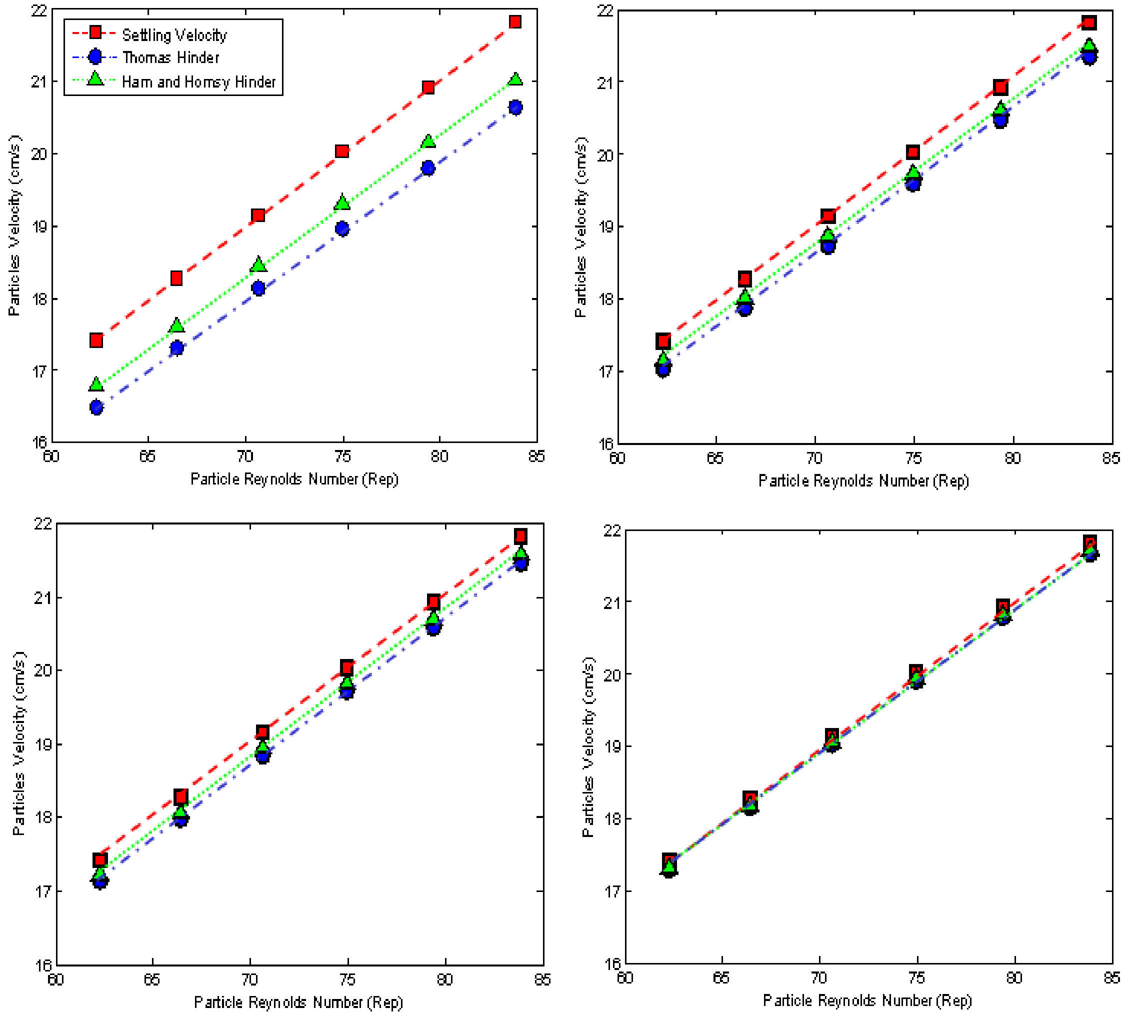


Figure 4-9: Case D, particles hindered settling velocity at (1) ROP/Ua=0.0069, (2) ROP/Ua=0.0028, ROP/Ua=0.0021 (3), (4) ROP/Ua=0.0008.

According to the schematic results shown in Figure 4-6, 4-7, 4-8 and 4-9, with increasing the sphericity by portion of 0.03 from 0.75 up to 0.90, it was recognized that always Thomas correlation gives relatively less hinder velocity values than those by Ham and Homsy's equation.

At the same annular size, the higher difference between settling velocities and hinder settling velocity was greatly encountered at the highest ratio of the ROP to the annular velocity $ROP/U_a$=0.0069. That indicates the significant role of cuttings concentration in the hindered behavior. Thus, under similar conditions and at low cuttings concentration the effect of the hinder behavior seems negligible, which is more significant at the lowest ratio $ROP/U_a$=0.0008.

According to the upper four cases, ignore of the hinder behavior of cluster of particles generated 5.60-0.70% error measured on Ham and Homsy's correlation. While returned 3.80-0.45% error based on Thomas correlation. Whereas, such errors as primary calculations able to disturb reliability of dependable calculations that may use as basis in design and/or operational tasks.

Cluster of cuttings found to behave lower settling compared to a single particle settling velocity, particle collision should carefully be considered especially at high cuttings concentrations and high sphericity. Since horizontal transport demonstrates higher cuttings concentration, it was recommended that hinder velocity correlations should be used to avoid errors regardless of settling velocity values or concentration.

### 4.4 Simulation Results

Ramadan et al. [3], presented a mathematical model on the particle flow in highly deviated pipe flow. Stevenson [47] commented on Ramadan et al.'s paper mentioning that, their model is extremely identical to the model of pipe flow by Doron et al. 1997.

However, in spite of that criticism, work by Ramadan et al. was used as base back ground for the presented model. In this research multiple changes were carried out on

Ramadan et al.'s model. Therefore, what is developed in the current research is entirely differ as shown in Table 4-5.

Table 4-5: Differences between the current model and previous models.

| Feature | Previous Models | Current Model |
|---|---|---|
| Section | Pipe/Eccentric | Concentric Annulus |
| Total concentration | assumed input | Calculated, $C_t$=f(ROP, $D_p$, $D_w$, $U_a$) [43] |
| Particle shape | Sphere | Irregular shapes (sphericity) |
| Diffusivity distance | $h_m$/100 | $2d_p$, FredsZe & Deigaard (1992) [3] |
| Fluid | Bentonite & PAC solution | Various Non-Newtonian muds |
| Settling velocity | Dedegil (1987) | Chien (1994) model [50] |

### 4.4.1 Basic Model Simulation Results and Discussion

Simulation results of the basic model are presented in (Appendix B) and analyzed in term of the examined parameters, which were, the annular mud velocity, the drilled cuttings size, the drilled cuttings shape, the fluid viscosity, the ROP and the annular geometry size, as shown in the following analysis:

#### *4.4.1.1 Effect of Annular Velocity on Cuttings Transport*

Regardless of all factors affecting on the process of the cuttings removal, simulation of horizontal transport indicated the great importance of the annular fluid velocity on the transport. This is clearly understood from the extracted correlations shown in (Appendix C). Li and Walker [25], recorded that, at all drilling modes the most important variable affecting the cuttings transport was the in-situ liquid velocity. The transport performance was parallel increase as annular flow velocity increases. For the range of the input data, where cuttings transport inspected in range of 0.75-6.3 ft/s annular velocity, the better hole cleaning was repeatedly recorded at higher annular mud velocities which reported to be occurred between 4.5-6.3 ft/s.

However, increasing the annular velocity returned thicker suspension layers at all cases, meaning that higher annular velocities guarantees considerable reduction on the cuttings bed layer. Increasing of the annular mud velocity enhanced removal of the stationary particles to travel to the upper moving-bed layer delivering thicker moving-bed layer as noticed in the moving-bed built up (Appendix C). This was also supported by Okrajni and Azar [20] , where they have reported that higher annular velocity intended to limit cuttings bed formation in the directional transport. As well, the results agrees with [27] and assured that high flow rate is quietly demanded in order to generate high shear force to erode cuttings beds.

*4.4.1.2 Effect of Cuttings Size on Cuttings Transport*

Through testing of three different particle sizes (large medium and small cuttings) increasing of the annular fluid velocity was also essentially to accomplish vanish of the stationary-bed layer. Highlighting that, existence of the moving-bed layer at a certain mud velocity did not mean vanishing of the bed layer corresponding to this velocity. Supposing that the moving-bed layer is considerable once $t_m$ became higher than/or equal to $d_p$, existence of true moving-bed layer at the different cutting sizes was considered as in Table 4-6.

As noticed in Table 4-6, higher annular fluid velocity is extremely required to terminate the bed layer. In case of large size of 0.25 in, moving-bed layer appears at relatively higher annular velocity compared to the case of smaller sized particles. The reason behind the difference in the bed termination velocity is related to the different requirements of the erosion at the upper surface of the bed-layer for the different cuttings sizes. Naturally high drags are demanded to overcome the opposite hindered forces of large sizes. For the smaller particles lower drag force are needed to erode cuttings from the upper surface of the bed, meaning that lower fluids velocity is required to do.

Table 4-6: The considerable velocity of the moving-bed layer and bed termination for the different particle sizes

| **Particle size (in)** | **$U_a$ (ft/s)** (at which true moving-bed layer existed) | **$U_a$ (ft/s)** (at which stationary-bed vanish) |
|---|---|---|
| 0.25 | 3.7 | 4.7 |
| 0.175 | 3.5 | 4.9 |
| 0.03 | 2 | 5 |

Under the same operating conditions and fluid viscosity, the termination velocity for large sized particles was 4.7 ft/s. While bed consisted of the medium cuttings with 0.175 in mean diameter, the bed layer vanish at 4.9 ft/s. For smaller cuttings of 0.03 in (correspondent to 0.76 mm), the bed-layer termination velocity was 5 ft/s. Duan et al. [36] suggested that the inter-particle force of small particles is dominated with forces that resist particles movement. Similarly Duan et al. [29] stated that, mechanism of small cuttings transport was more complicated than of the larger particles due to their stronger particle-particle intra-phase and interaction as well as particle-fluid intra phase interaction. Therefore, additional annular velocities are required to remove all small cuttings from the stationary-bed.

At the same annular velocity, suspension concentration of the small cuttings was much higher than of the medium and large cuttings sizes. In instance, at annular velocity 4 ft/s the predicted cuttings concentration for the small, medium and large sizes was 0.356, 0.047 and 0.034 respectively. Thus, small sized particles were more welling to be suspended. This is logical and clearly visible in Figure 4-10.

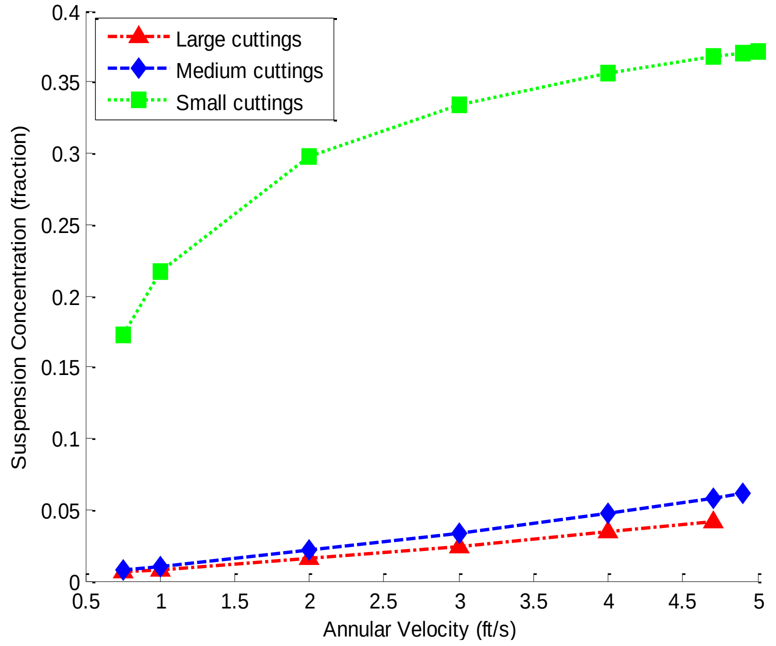


Figure 4-10: Effet of annular velocity on suspended layers concentration at different particle sizes

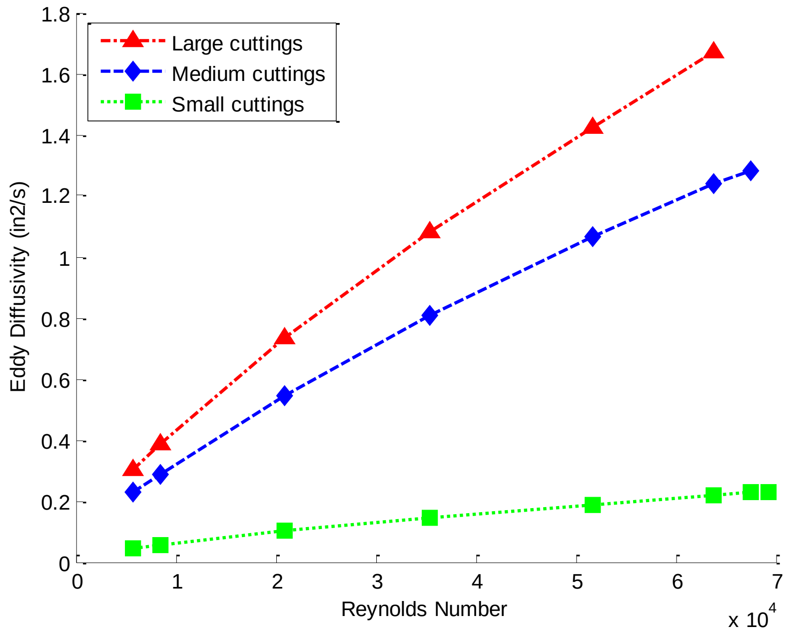


Figure 4-11: Eddy Diffusivity of the different particle size

The evaluated eddy diffusivity as function of particle size showed in Figure 4-11. This figure specifies that higher eddy diffusivity was needed by the large sized particles.

Altunbas et al. [70], concluded that eddy diffusivity of particles in horizontal flow increase as their sedimentation velocity increases, where it is confirmed that larger cuttings exerting high settling velocities. Therefore large particles demanded to generate higher eddy diffusivity than of small ones. Accordingly, diffusivity of cutting particles enlarges with their size. This truth is also visible through formula of the eddy diffusivity at [17] where the eddy diffusivity coefficient of cutting is enlarges with their size.

As shown in Figure 4-12, at equivalent annular velocity, transport of large and medium cuttings size exerted less shear stress ratio at the bed surface compared to the small size which is agrees with the trend observed by Ramadan et al.

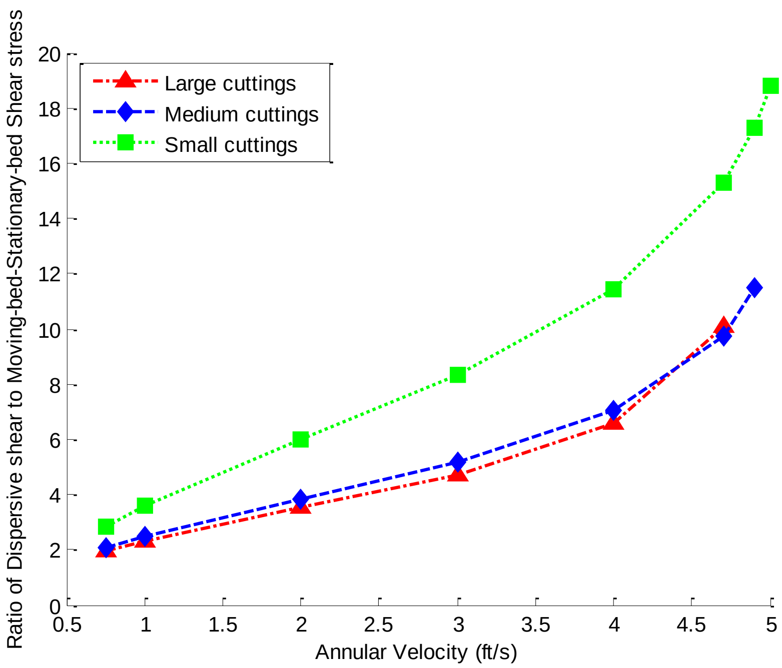


Figure 4-12: Ratio of the bed layers shear stress for the different cuttings size

Figure 4-13 shows the predicted pressure drop along the annulus at various annular velocities. Large sized particles needs to apply more pressure force to be transported.

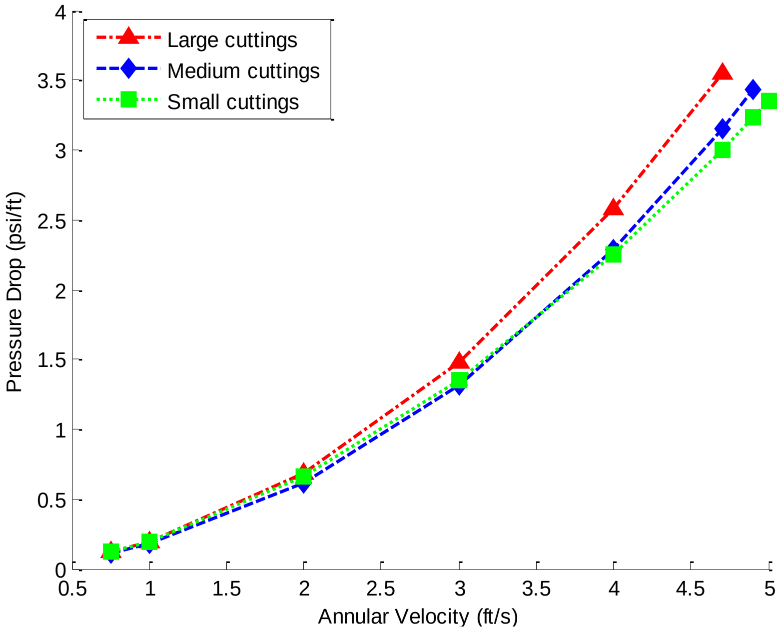


Figure 4-13: The pressure drop predicted at the different particle sizes

It can be said that below annular mud velocity of 3 ft/s, almost there is no sensible contribution for different cuttings sizes on the pressure drop. However, over the entire applied annular velocities, it could be concluded that at certain range of annular velocity the size of cuttings do not affect the value of the pressure drop in considerable amount. Hence, the most influenced parameter in the increment of the pressure drop is the annular fluid velocity. Furthermore, dimensionless analysis was carried out as shown in (Appendix D).

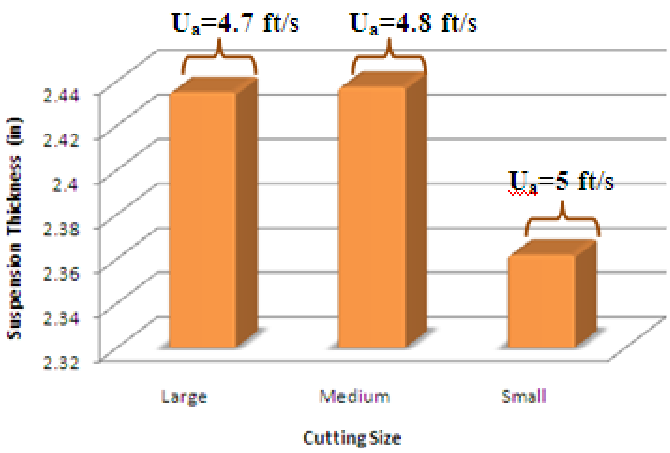


Figure 4-14: Final suspension layer of the three cuttings sizes at maximum cleaning

Figure 4-14 presented a zoom in view on the thickness of the suspended layer under different particles sizes. The figure confirmed that, height of the suspension of the small sized cuttings is lower than in case of large and medium sized particles.

Built up of the moving-bed layer is an indication for the particles transfer from the stationary-bed as shown in Figure 4-15. Due to the velocity flow, eddies will be generated at the bed surface consequently the shear force enhance transport of the cuttings particles to the upper layers. Here also annular velocity of the carrier fluid plays the significant role to move the stationary cuttings.

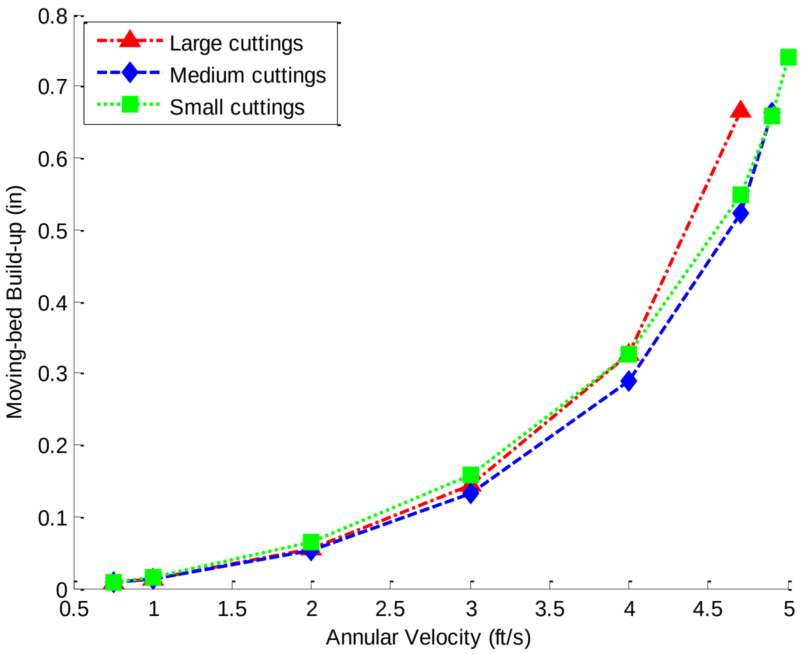


Figure 4-15: Moving-bed layer growth under increasing annular velocity

Once stationary-bed vanishes, two layers remains as suspension and moving-bed layer. At this point the transport performance of each layer is shown in Figure 4-16, for the large, medium and small particles as percentage of initial and resulted layers.

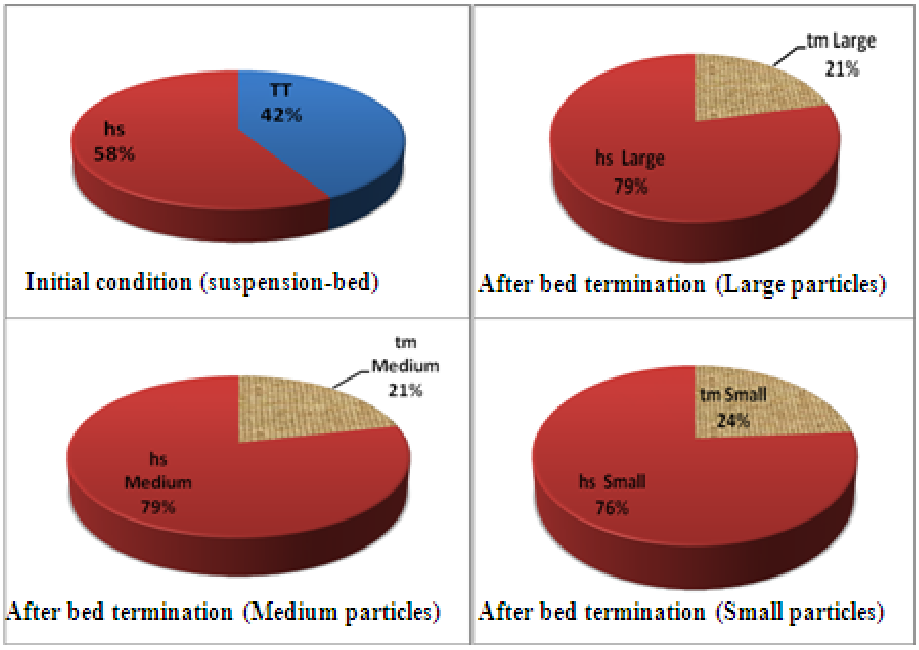


Figure 4-16: Percentages of moving-bed thickness before and after cleaning for the different particle sizes

However, in term of the required annular velocity transport of the largest cuttings was much efficient since it was generate high suspension at lower velocity. But still transport performance of the small sizes seems more easy since it is more responsive to the turbulent eddies and became easily suspended in term layers concentration that agrees with Ford et al. [22]. Through their different studied cases, Walker and Li [26] also reported that lager cuttings were harder to be clean out of the hole.

Generally, during looking on the several studies targeted to inspect the effect of the cutting size, it was perceived that, it is difficult to underline either small or large cuttings is easier to be removed. This is very impressive conclusion since different studies arrived to diverse results regarding this parameter. However, Duan et al. [71] suggested that difficulty to transport small cuttings occurs where low viscous fluids were in use.

*4.4.1.3 Effect of Particle Sphericity on Cuttings Transport*

According to the preliminary investigation particle shape is considerable factor in the particle settling behaviour. Their results are in broad agrees with Ozbayoglu et al. [69], as presented in the preliminary results on chapter six. Advanced examination of effect of cuttings shape on the transport was carried out by changing the cuttings sphericity from 0.75 upto1 in steps of 0.05 increments. It was previously mentioned that the common sphericity of drilled cuttings is between 0.75 to 0.85. For the sake of comparison with the standard sphere, cuttings sphericity of 0.95 and 1, was also considered in the present analysis.

To reach the maximum bed removal for the similar cutting size of 0.25 inches near to 0.95 and 1 sphericity, cuttings bed demanded extra annular velocity rather than the velocity required by less cuttings sphericity.

It is well known that drag coefficient of the sphere is less than of non-spherical particle [4]. Hence, regularity of particle shape initiates mandatory increase in the velocity required to obtain the demanded drag force to move the regular sphere. As per the schematic sketch shown in Figure 4-17, the smoother sphere surface is in conjunction with regular slope lines. Hence, slippage of the smoother particle is faster than for non-smoother shaped particle. Irregularity in particle shape stuck the slip lines and lowers its settling behaviour and thereby lower transport velocities are qualified to suspend the irregular shaped particle. Furthermore, Saasen et al [72], specified that due to the porosity of cutting particles, the formed bed would have some kind of loose which greatly helps to remove the settled cuttings.

Figure 4-17: Slip lines on particle of regular and irregular shape

As shown in Figure 4-18, as cuttings shape became irregular, suspending of the cuttings is easier. With high sphericity, cuttings exerted lower suspension concentration. In instance, difference of 0.2 in, on the particle sphericity resulted in 0.0133 difference in suspension concentration at the same annular velocity 4.7 ft/s. Thus, assuming regular shape for cutting particles returned around 27-23% error in suspension concentration based on 0.8 sphericity factor.

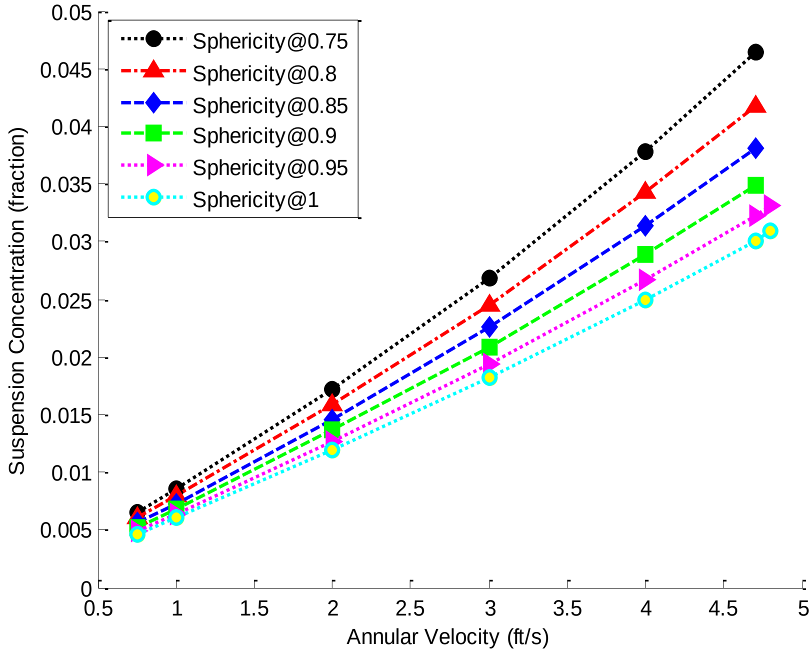


Figure 4-18: Effect of sphericity on the suspension concentration during cuttings transport

Precise result of the suspension thickness presented in Figure 4-19, showed that increase of the particle sphericity from 0.75 to 0.9, caused slight increase on the thickness of the suspension layer. For the cuttings sphericity range 0.75- 0.9, the maximum velocity required to transfer all cuttings from the stationary-bed to the upper layers was 4.7 ft/s. Whereas reversed behaviour was recognized at sphericity 0.95 and 1, which exerted much lower suspension thickness at same higher velocity of 4.8 ft/s, that followed by increase in the moving bed thickness. Perhaps this was also happened due to the slippage at high sphericity. That is very interesting and enhances importance of further investigation on the sphericity effect.

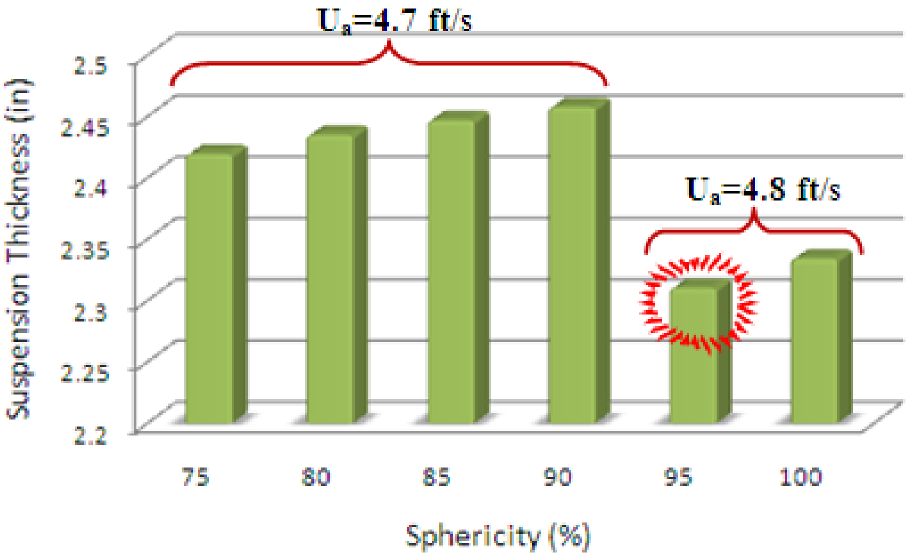


Figure 4-19: Suspension thickness at the bed termination condition for different cuttings sphericity

However, among the tested shape factors, cuttings with 0.95 sphericity was the unlikely shaped particle compared to the sphere since it altered the lowest suspension layer as shown in Figure 4-19.

*4.4.1.4 Effect of Fluid Viscosity on Cuttings Transport*

The described four types of mud demonstrated that performance of the cuttings transport increases with the annular fluid velocity and fluid viscosity. The experimental results obtained in [22] stated that increasing of the viscosity assisting the hole cleaning.

Figure 4-20 showed that lower mud's viscosity were more able to catch the same cuttings to the upper suspension layer.

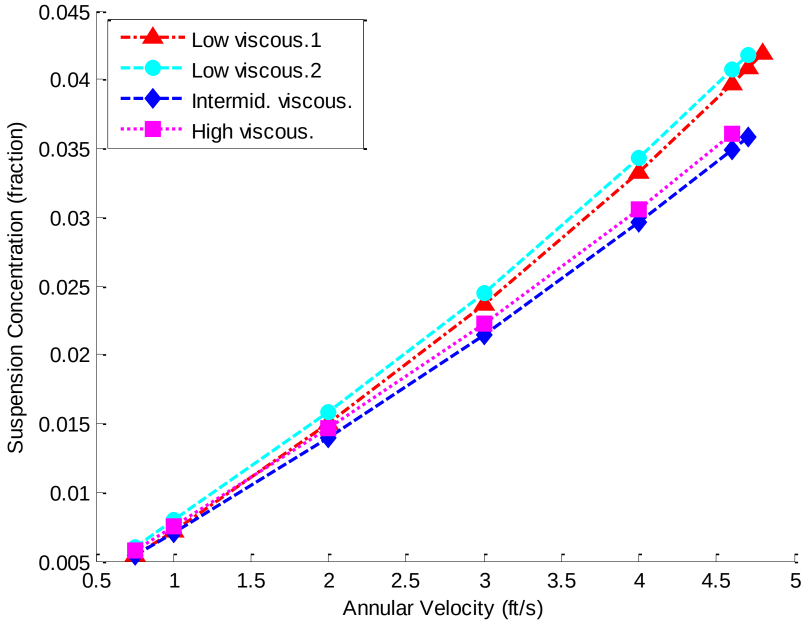


Figure 4-20: Suspension concentration under different mud viscosity

Higher viscous fluid resulted in higher pressure drop relatively. Increase of the viscosity of the fluid returned higher frictions as shown in (Appendix D). Low viscous fluids exerted higher shear stress ratio at the bed surface compared to the intermediate and low fluid viscosities. As shown in Figure 4-21 and 4-22 respectively.

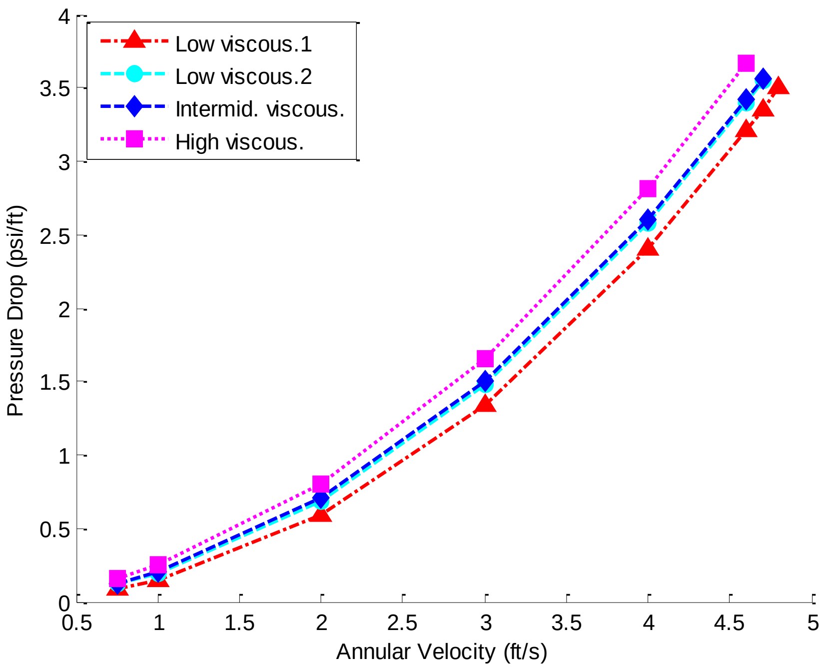


Figure 4-21: Pressure gradient at different power law viscosities

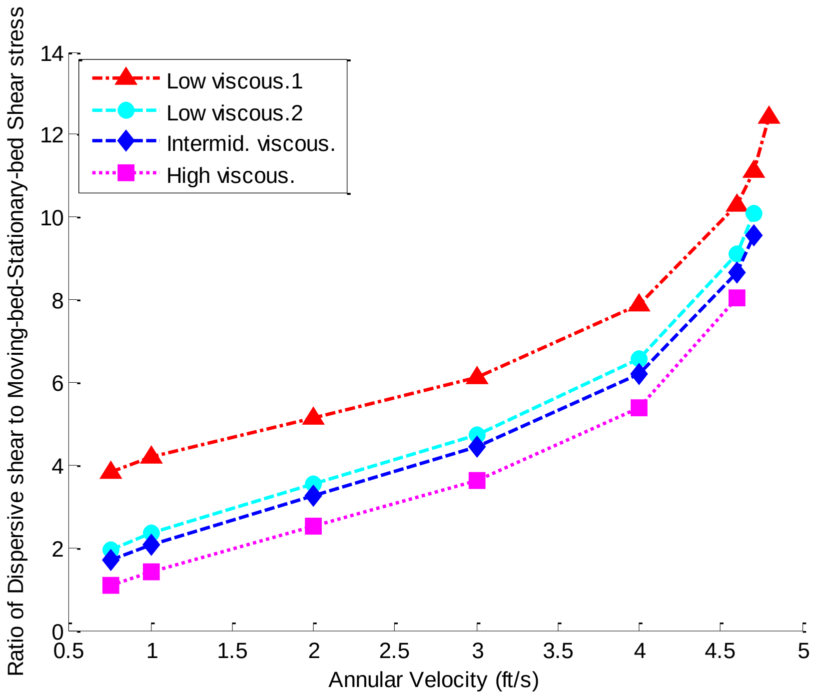


Figure 4-22: Effect of the fluid viscosity on the exerted shear stress

Previously Nguyen and Rahaman [43], suggested that contribution of rheology comparing to other parameters may have lower effect, but this do not erases the noticeable effect of rheology in the transport. Recently, case studies and analysis of 75 wells done by Shahbazi et al. [73], proved that rheology and other properties of drill-mud are closely related to the stuck pipe problem. Using try and error, the mud properties and mud equipments employed to arrive at a reducing stuck index, or, RSI, which is recommended to be in focus in order to mange this problem.

From Figure 4-23, once cuttings of the stationary bed layer transferred to the upper layers by means of high viscous mud of $K$=0.00084 lbf.$s^n/ft^2$; $n$=0.68, thicker suspension of 2.454 in, which became slightly thinner as viscosity reduced to $K$=0.00084 $lb_f.s^n/ft^2$ and $n$= 0.68.

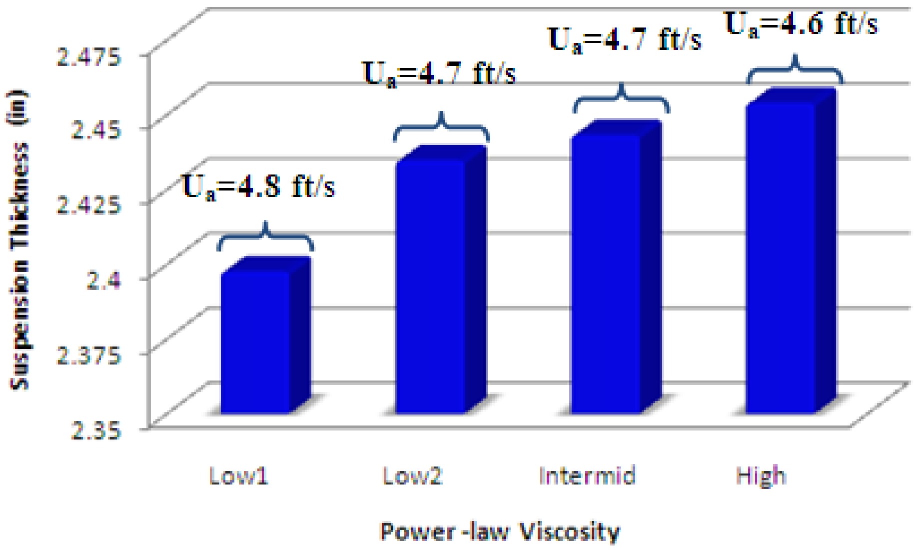


Figure 4-23: The Maximum suspension thickness reached with different mud viscosities

From one side view, high viscous non-Newtonian mud was the best media to transport horizontally since it enables cuttings removal from the bottom bed layer to the upper moving bed and to the suspension layers better than low fluid viscosities. Thereby, high mud viscosity provided thicker suspension at lower annular velocities 4.6 ft/s as shown in Figure 4-23.

On the other hand, important observation on the Reynolds number was realized in the tests of the fluid viscosity, where high viscous fluids exerted less Reynolds numbers. This agreed with observation by Cho [4], where he noticed that viscous fluids are qualified to suspend transported cuttings longer. But, functionality of the horizontal transport efficiency is built on both time and turbulence in parallel. Balance between fluid properties and velocity must handle with more attention at horizontal orientation. Increase of the fluid viscosity causes reductions on the Reynolds number. Therefore it will be harder to obtain the required turbulent conditions. Accordingly in case of highly inclined to horizontal transport relatively low viscous fluid is recommended to achieve the required flow rates as advised by Ozbayoglu et al. [69].

Walker and Li [26], concluded that fluid rheology plays an important role in the transport, and agreed that low viscous fluid with turbulent flow was the best way to pick up cuttings.

Furthermore, Saasen et al. [72], suggested that drilling fluids should be optimize in their design to minimize the gel formation on the bed as much as to ensure sufficient shear stress on cuttings to be removed. As viscosity and gel strength of mud decrease, formations of the gel on the cuttings bed will be decrease. As consequent this lead to improve the hole’s cleaning. Adari et al. [31], mentioned that for a given drilling fluid flow rate, lower cuttings bed height is achieved as the n/K ratio increases. This means that cuttings removal is enhanced by reducing the viscosity of the fluid. It was also observed that increase of the fluid flow/annular velocity has a noticeable impact on transport, since it caused faster bed erosion.

#### *4.4.1.5 Effect of Rate of Penetration ROP on Cuttings Transport*

Supported by results of the layered model by Gavignet and Sobey [40], lower effect was accounted for the applied ROP. Meaning that varying of the operational ROP has no observable influence on the performance of cuttings transport.

Within the tested range of rate ROP (60, 50, 30 and 15 ft/hr), very small difference was observed in the suspension concentration. At the same annular velocity, the lowest ROP 15 ft/hr, demonstrated suspension concentration of 0.0420, while the highest ROP 60 ft/hr, a 0.0418 suspension concentration was recorded.

However, increasing of the annular velocity, increase the suspension concentration with reduction of the ROP. In spite of the small difference registered on the suspension concentration under different ROP, the obtained results are satisfied with the results achieved at [56] it was observed that concentration of the cuttings in the annulus dropped with decreasing of the ROP.

Moreover, increasing of the ROP from15 ft/hr up to 60 ft/hr has intangible impact on the maximum annular velocity to achieve complete bed erosion, since all applied ROP demanded the same termination velocity of 4.7 ft/s. Hence, the predicted results through this model indicated that cuttings transport was not much sensible to the ROP as compared to other affected parameters.

Despite of the weak effect of ROP in cuttings removal, zooming into suspended layers reflected little difference of suspension thickness. Results shown in Figure 4-24, captured a thicker suspension layer at the higher ROP 60 ft/hr, while lowest ROP 15 ft/hr, had the thinner suspended layer. Ozbayoglu et al. [69] supporting that the operated ROP has a slight effect on the bed thickness. Furthermore, he suggested that contribution of the ROP is related to the issue of time rather than in cuttings removal.

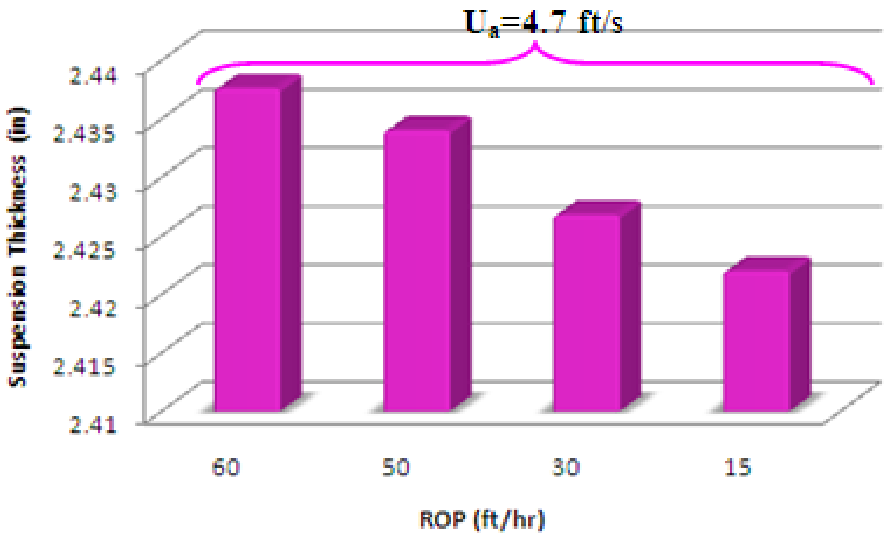


Figure 4-24: Maximum suspension thickness under different ROP

The prediction of the total cuttings concentration $c_t$ in the annulus at different ROP is shown in Figure 4-25. Total concentartion created by the drill-bit increase as ROP increases. It was also relized that, as much as pumping flow velocity increases high reduction in the total concentration is occurred, mainly after annular velocity 2 ft/s. Meaning that to control high concentartion in annulus high annular velocity will be required.

While high ROP is preferable to be adopted in the drillings fields for the sake of time, high ROP increase the cuttings concentration in the annulus. If the limits of this increase compensate the sequential problems of the cuttings accumulation, Azar and Sanchez [74] claimed that the only one alternative is to reduce the ROP.

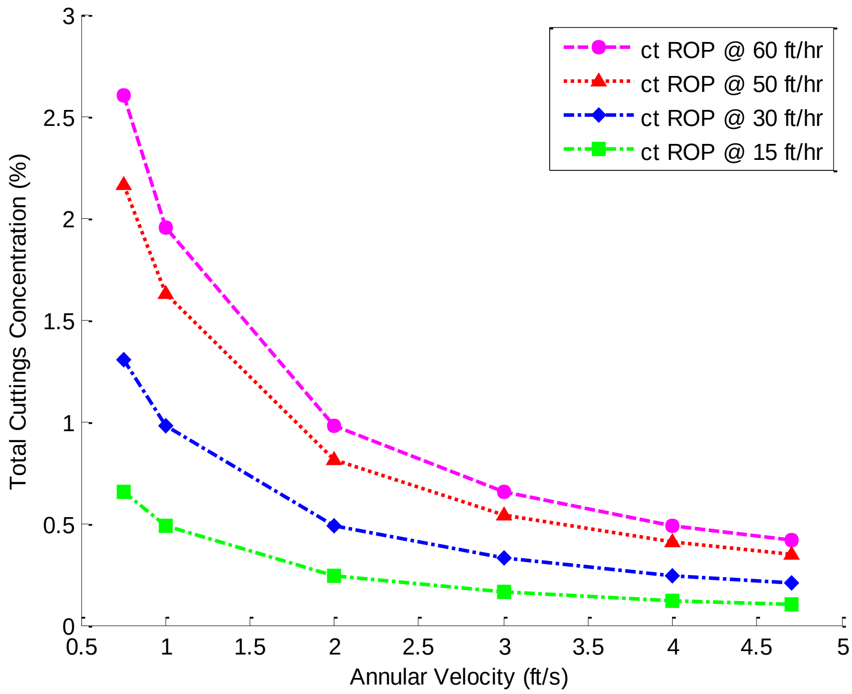


Figure 4-25: Effect of the operational ROP on the total cuttings concentration exerted in the annulus

#### *4.4.1.6 Effect of Annular Size on Cuttings Transport*

The obtained results for the four different annular sizes involved in the recent analysis are in close agreement with recent results from [40, 42] and [75].

Table 4-7: Dimension of the different annular Sizes

| $D_p$ (in) | $D_w$ (in) | $0.5(D_w\text{-}D_p)$ (in) | Area ($in^2$) | Bed Termination Velocity $U_a$ (ft/s) |
|---|---|---|---|---|
| 2.375 | 5 | 1.3125 | 15.2064 | 4.5 |
| 1.9 | 5 | 1.5500 | 16.8048 | 4.9 |
| 4.5 | 8 | 1.7500 | 34.3728 | 5.8 |
| 4.5 | 8.75 | 2.1250 | 44.2368 | 6.3 |

For the entire targeted unknowns in the presented model, change in the annular size was a considerable parameter since its altered countable differences in the required annular velocity, suspension concentration, pressure drop as well as the dispersive shear stress.

Considering Table 4-7, lower annulus area or smallest annular gap reflected higher suspension concentration, pressure drop and dispersive shear stress, as per Figures 4-26, 4-27, and 4-28, respectively.

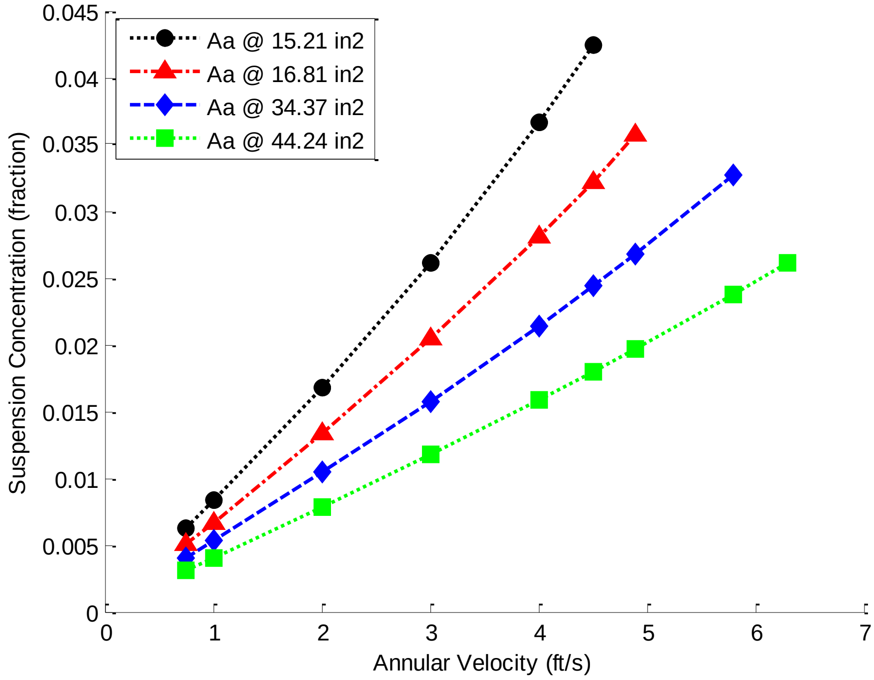


Figure 4-26: Effect of the different annular size on the suspension concentration

Figure 4-27, shows a broad reduction on the pressure drop as annular area increased. Annular velocity required to transport all cuttings from lower bed layer to the upper moved layers increase as annular area increase. The required annular velocity to completely remove the cuttings bed was higher for the large annular area which reached 6.3 ft/s. Such velocity seems to be very high that wellbore erosion may occur.

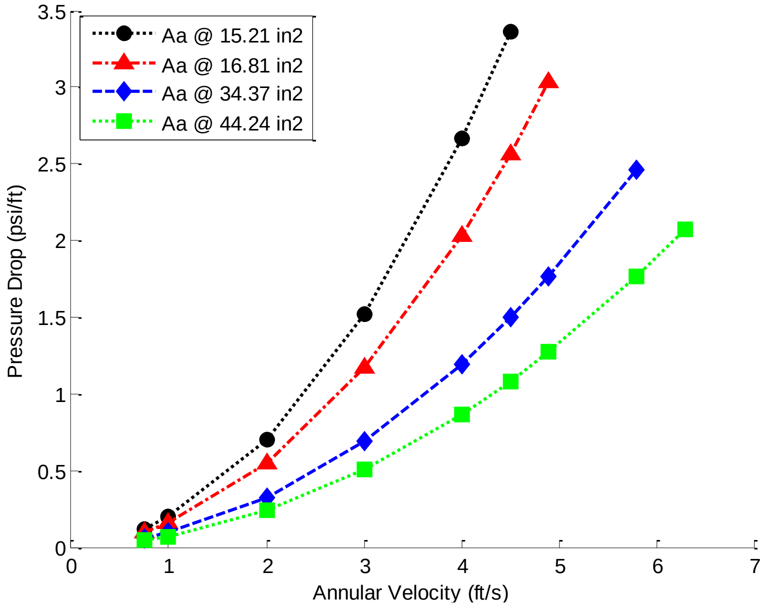


Figure 4-27: Effect of the different annular sizes on the pressure drop

In addition, due to the pressure limitations the reported lower pressure gradient in the case of larger annular area could limit achieving of good transport performance. This result is in conformity with conclusion from [25].

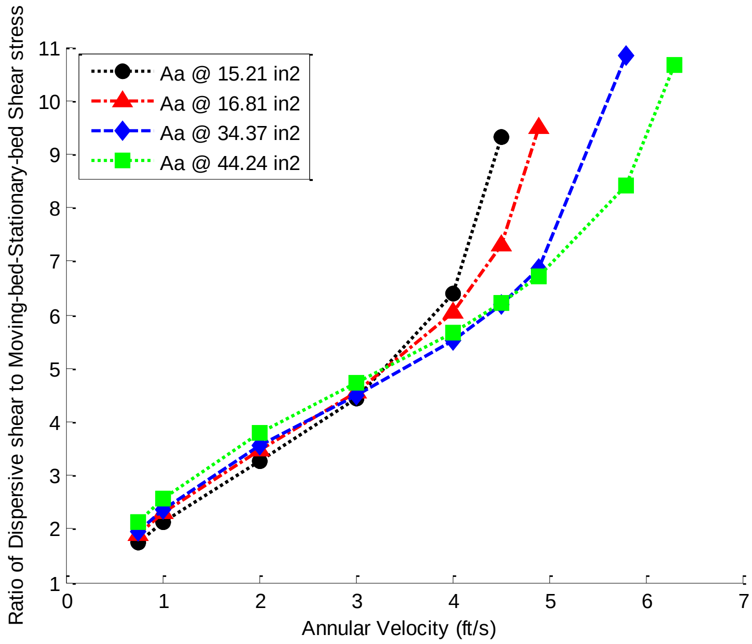


Figure 4-28: Effect of the different annular sizes on the ratio of shear stress.

In term of transport performance showed in Figure 4-29, to obtain the optimal cleaning the required annular velocity increases as annular area (gap) increased.

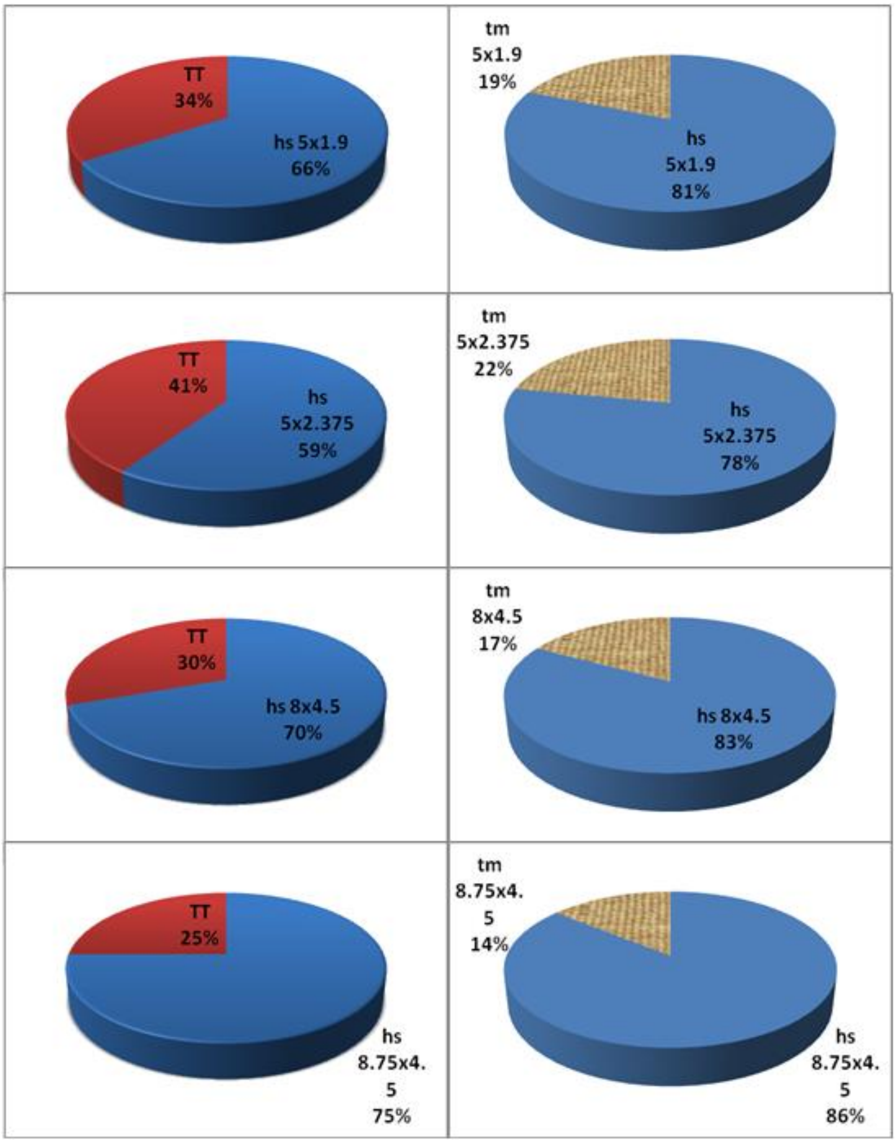


Figure 4-29: Comparison of final cleaning performance for the different annular sizes

For the same pipe size according to the ratio of the well annular ($D_p/D_w$), given in Table 4-8, the lowest ratio demonstrates lowest total cuttings concentration and vice virca, as shown in Figure 4-30. Obviously, it was remarked that the additional increasing on the suspemsion layer $\Delta h_s$ was also related to this ratio, where the largest additonal suspension thickness $\Delta h_s$ is occured at the smallest ratio and vice versa as shown in Table 4-8. For the same bed height 1.0632 in, growth of suspension layer was faster at low annulus sizes.

Table 4-8: Increasing of the suspension thickness under the different annular sizes

| **Annular Ratio $D_p/D_w$** | **Bed Termination Velocity $U_a$ (ft/s)** | **$c_t$** | **Increase in suspension $\Delta h_s$ (in)** | **$t_m$ (in)** |
|---|---|---|---|---|
| 0.48 | 4.5 | 0.0040 | 0.487 | 0.576 |
| 0.38 | 4.9 | 0.0033 | 0.504 | 0.560 |
| 0.56 | 5.8 | 0.0035 | 0.412 | 0.652 |
| 0.51 | 6.3 | 0.0030 | 0.456 | 0.607 |

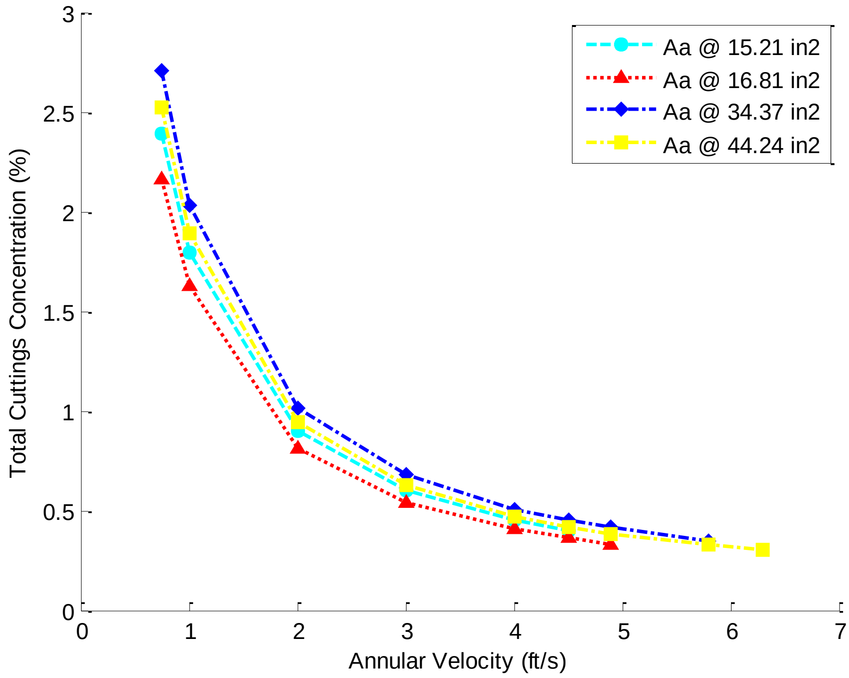


Figure 4-30: Change of total annular cuttings concentration at the different annular size

According to the observation on the annular gap and annular ratio, the lowest annular size (2.75x5 in), is most efficient size among the tested sizes since it is demonstrates higher suspension at lower annular velocity combined with higher suspension concentration. Accordingly it can be recognized that lower annular size is the better. Typically, findings from [42], agreed that increase of the drill pipe diameter would effectively solve the drilling problems, and that classifying the annular size as one of the controllable factors to gain smooth transport of cuttings.

Recall Figure 4-25, sensitivity of the total exertied cuttings by the bit to the annular size Figure 4-30 is lower compared to its sensitvity to the different ROP.

### 4.4.2 The Modified Model Simulation Results and Discussion

Proper selection for the inputs data is a key variable to achieve sufficient accuracy on the output results of the modelled phenomena. As well, technical selection of the mathematical calculation media represents a vital factor to attain rational outcomes which could be confidently valid in purpose of prediction.

As extra test for the developed model, the additional simulation aims to examine the influence of alternative equations available in the literature of the three layers models of cuttings transport. Contrasted equations by Doron et al. 1993 and Martin et al. 1996 are used in order to calculate the friction factors in the layers boundaries. In order to conduct direct comparison, same inputs data used by Cho [4] was adopted to perform this simulation.

#### *4.4.2.1 Effect of Annular Velocity on Cuttings Transport*

Through the modified model interesting observation were noticed in the behaviour of the moving-bed layer with an incremental annular velocity. As recorded in Table 4-9, and shown in Figure 4-31, very thin moving-bed layer appeared at very low annular velocity. The Moving-bed layer is dramatically increased with increment annular velocity up to have a considerable thickness at annular velocity 1 ft/s. The layer continues enlarge and reach its maximum thickness at annular velocity 1.9 ft/s. Then the observed moving-bed is gradually diminished and entirely disappeared at annular velocity around, 3.5 ft/s.

Table 4-9: Simulation results of the modified model

| $U_a$ (ft/s) | $U_s$ (ft/s) | $U_m$ (ft/s) | $t_m$ (in) | dp/dz (psi/ft) |
|---|---|---|---|---|
| 0.25 | 0.3085 | 0.0380 | 0.000216 | 0.001068 |
| 0.5 | 0.6379 | 0.0701 | 0.000324 | 0.002495 |
| 0.75 | 0.9676 | 0.1016 | 0.000396 | 0.004439 |
| 1 | 1.2972 | 0.1328 | 0.000444 | 0.006928 |
| 1.5 | 1.9592 | 0.1954 | 0.000504 | 0.013622 |
| 1.75 | 2.2895 | 0.2265 | 0.000504 | 0.017813 |
| 1.9 | 2.4865 | 0.2450 | 0.000504 | 0.02057 |
| 2 | 2.6198 | 0.2576 | 0.000492 | 0.022576 |
| 2.5 | 3.2751 | 0.3188 | 0.000444 | 0.033714 |
| 3 | 3.9344 | 0.3806 | 0.000348 | 0.04721 |
| 3.5 | 4.6023 | 0.4437 | 0.000204 | 0.063239 |

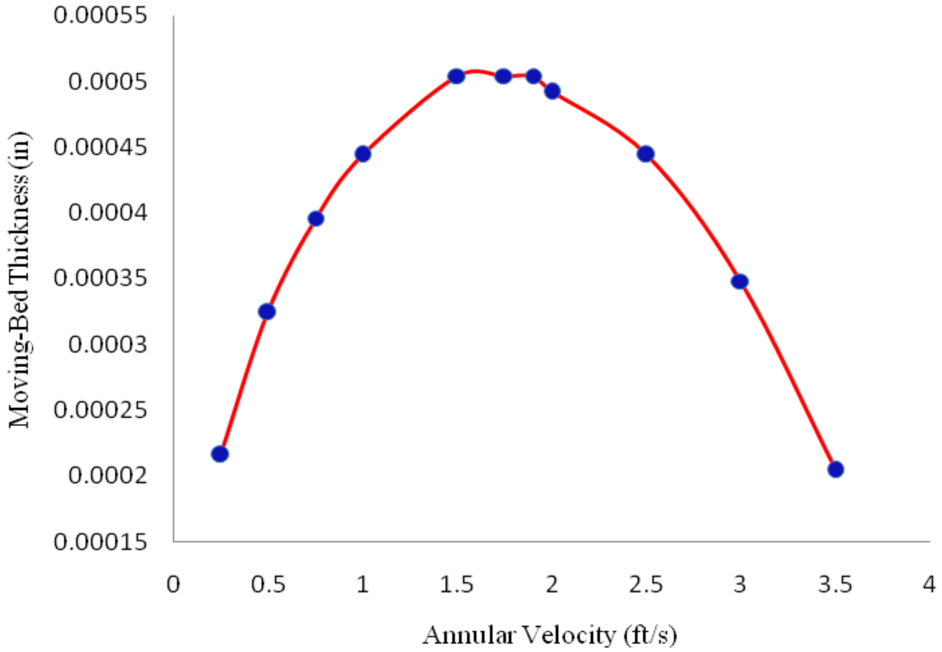


Figure 4-31: Moving-bed behavior-modified model

As shown in Figure 4-31, the highest moving-bed thickness was recognized at velocity of 1.9 ft/s, which near to the observation Cho [4] who characterized this phenomenon in eccentric annular to be occurs between velocities 2-3 ft/s. However, the obtained values for moving-bed thickness in his case were much larger than the values obtained in this study.

#### *4.4.2.2 Effect of Friction Factor on Cuttings Transport*

Changing of the friction factor evaluation altered considerable change on the moving-bed behaviour and thereby the combinations of the transport layers. Change of the friction factor formula influence on the transport performance and accordingly two different tracks achieved as shown in Figure 4-32.

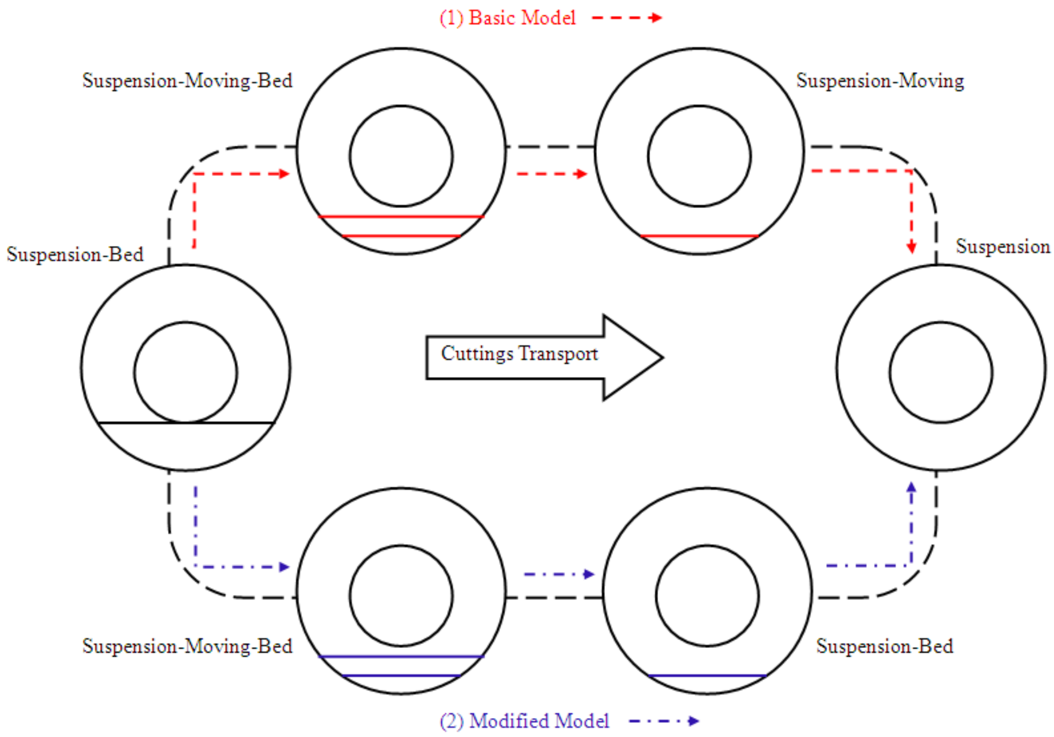


Figure 4-32: Basic and modified simulation tracks

To reach the desirable cleaning removals through single suspension layer, each of the two models used different combination of two layers. Thus, mass transfer through the basic model vanish the bottom stationary bed layer by exerting suspension and moving-bed layers. While the modified model attempt to reach the suspension layer without the transition stage i.e. the moving-bed layer, this model resulted in suspension and stationary-bed layer to reach the bed removal.

Weather the first or the second behaviour of moving-bed would be occurred was extremely depended upon the friction factor correlation. Hence, replacement of Szilas correlation to calculate the friction factor between layers and between layers and boundaries effectively returned the influence of the friction factor on the three layers behaviour. This is clearly reflects sensitivity of the modelling technique to the empirical equations, where chosen of unsuitable equation is qualified to distort the simulation entirely, and it may reflect improper behaviours which could never be confident in purpose of prediction.

### 4.5 Models Contrasting and Validation

Iteration technique of the basic model demands an existence of three layers. This is physically true since logically there are no direct cuttings edges between a suspension and dead layer. In other words, $t_m$ might never be equal to zero when there is particle interaction and exchange between the layers according to the diffusivity theory. Long et al. [76], stated that removal of the bed depend upon the moving-bed that supports findings by Ramadan et al. [3] as adopted by Figure 4-33.

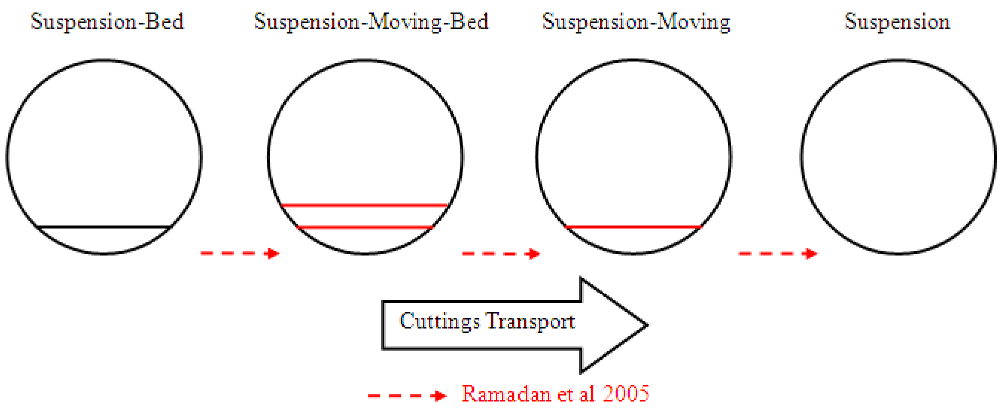


Figure 4-33: The contrasted transport track on pipe flow

Approximation of the moving-bed hydraulic diameter by the suspension hydraulic diameter was necessary because using of the direct calculated hydraulic diameter from the moving-bed flow area and perimeters disturbs the model solution. Same fact was mentioned in [3].

The scenario of the moving-bed layer appearance and hiding at 3.5 ft/s agrees with moving-bed layer trend obtained by Cho [4], at velocity of around 4 ft/s. This also satisfied the criteria of the dispersed suspension.

On the other hand results by Nguyen and Rahman [43], seem to be typical to those observed by Cho [4] as described by the sketch in Figure 4-34. Therefore it is difficult to judge which one of the two directions is the correct. Hence, it is extremely essential to know which layer will survive to transfer cuttings to the upper suspension during the transport.

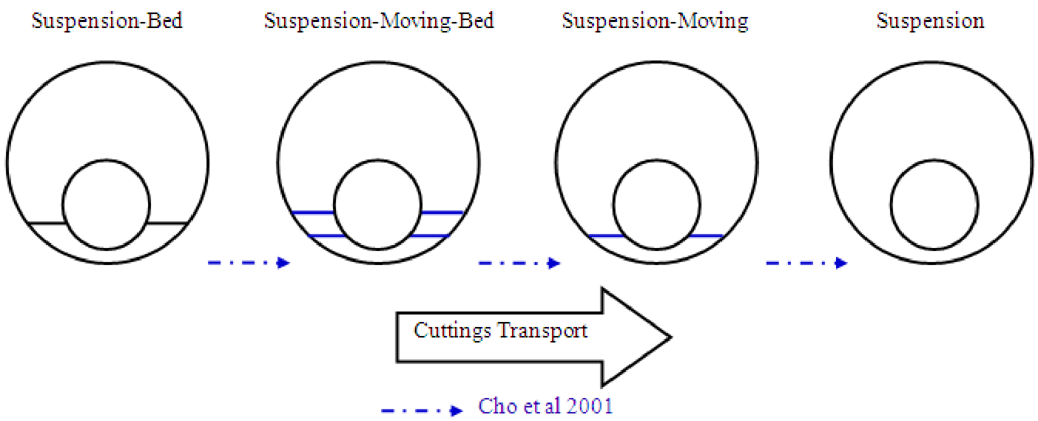


Figure 4-34: The contrasted transport track on eccentric annulus flow

Through examination of the particle size effect, the obtained results of the pressure drop and result of $\tau_{dis}$ to $\tau_{mb}$ ratio have demonstrated similar concept as what was reported by Ramadan et al. [3].

Generally it may recognize that to somehow basic model obtained high values of Reynolds numbers. These values are acceptable when they compared to the values reported by Ramadan et al [3]. Thus, in pipe of 2.76 in (70 mm) diameter the maximum flow velocity values was less than 3.9 ft/s (0.6 m/s), which is relatively low compared to the maximum values required in the annulus.

Performance of the modified model to simulate the cuttings transport is still weak. Installation of the modified model was held through the model at [3]. The frictional equations implemented in the modified model are same to previous model Cho [4], where estimation of the wall shear and interfacial shear equations in these models (3-8), (3-9), (3-19) and (3-20) is lower than previous studies. Therefore, it might be inconsistent to examine the moving-bed behaviour observed at [4] on the approximated bases. However, the modified model succeeds to capture the trend of the moving-bed layer as well as Cho model.

Table 4-10: The moving-bed thickness under the concentric and eccentric annulus

| **Current Model** | | **Cho et al 2001** | |
|---|---|---|---|
| **$U_a$ (ft/s)** | **$t_m$ (in)** | **$U_a$ (ft/s)** | **$y_m$ (in)** |
| 0.25 | 0.000216 | 0.75 | 0 |
| 1 | 0.000444 | 1 | 0.01 |
| 1.9 | 0.000504 | 2 | 0.32 |
| 2.5 | 0.000444 | 3 | 0.2 |
| 3.5 | 0.000204 | 4 | 0 |

Table 4-10, compares the results obtained through the current model and Cho[4]. As shown in Figure 4-35 and 4-36, low thickness for moving-bed layer was predicted in the concentric annulus compared to the eccentric. Low thickness for moving-bed can be explained through the area distribution at the different locations of the drill-pipe. Where concentric annulus had the similar dimensions along the well, the eccentric annular had less area below the drill pipe surface. Hence, for the same well and drill pipe, moving-bed layer having a wider area should exert less height. However, Kamp and Reviro [39], mentioned that eccentric position of annulus would increase the bed height.

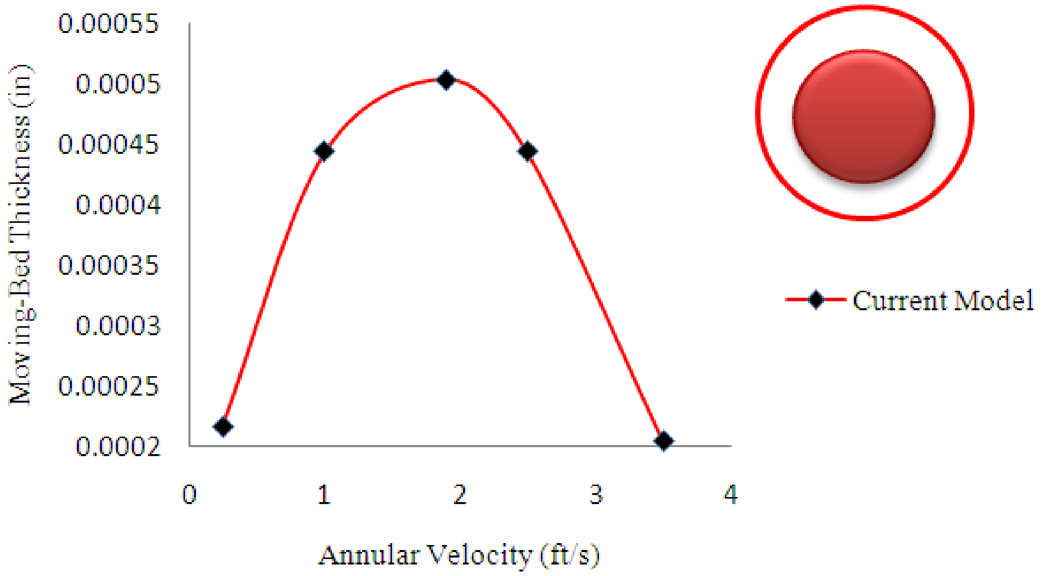


Figure 4-35: Moving bed behavior (Current model)

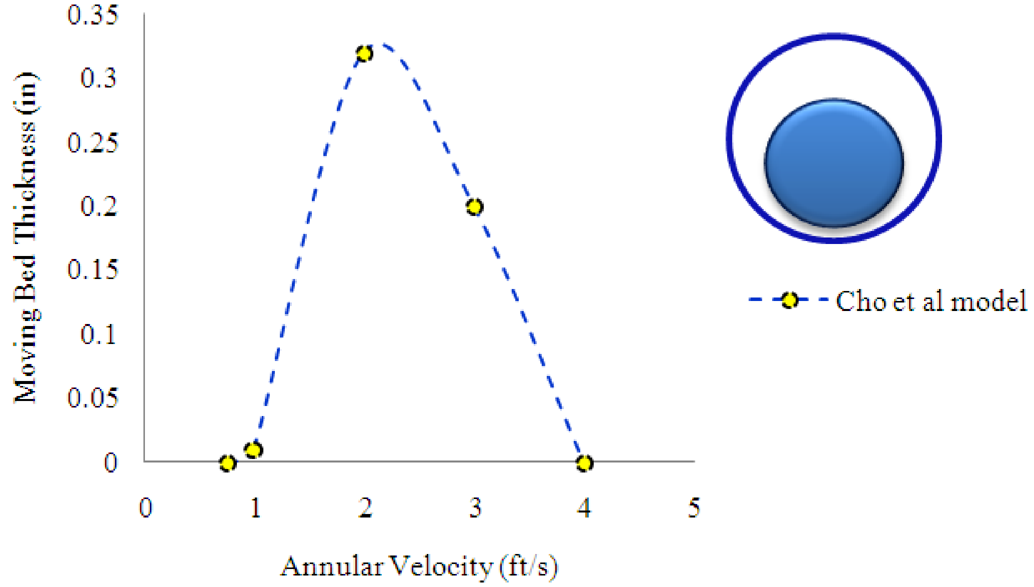


Figure 4-36: Moving-bed behavior (Cho's Model [4])

However, lower than 3 ft/s performance of the annular mud velocity exerts less pressure drop and less portion of the stationary cuttings are willing to transfer to the upper layers compared to the annular velocity higher than 3 ft/hrs. Therefore agreeing with [4], annular velocity range between 3-4 ft/s is preferable to enhance bed movement at quite suitable pressure drop and save the borehole and tools from wear and erosion effects. Generally, the obtained results demonstrate suitability of the model for the effective design.

### 4.6 Summary of the Modelling Results

This chapter present and discuss the obtained results. Using Chien's settling velocity equation to investigate the particle settling behavior under different particles sphericities the results demonstrated that large sizes and high density of drilled cuttings companied with regularity of shape motivate faster settling. In term of the fluid properties low fluid viscosity and density compensated the settling behavior.

Furthermore results of the particles hindered behavior investigation was much pronounced at high suspension concentration. Such analysis could be helpful in the field of cuttings transport specially in drilling application simulations. The analysis was tangent the valuable positions of the settling velocity and assessed prediction tool to judge where hinder settling effect should be taken with sufficient consideration in the transport modeling.

The results of the different casts of models equations presented and discussed separately. Cuttings transport simulation results for the seven targeted unknowns were predicted under the basic model. The parametric results captured the effect of cuttings size and shape, annular size, ROP, and fluid viscosity in the horizontal transport and compared to others findings. The ROP ranked lowest effect whiles cuttings size, annular size, and rheological viscosity of the drill mud returned considerable effects on the horizontal transport. Besides, the modified simulation under contrasted empirical frictional factor correlations resulted in different behaviour for the middle moving-bed layer. To achieve the horizontal cuttings transport, the annular mud velocity was the most effective factor on the transport performance.

However the two models were informative. The simulations results proved the capability of the basic model to estimate the influence of the drilling parameters on the transport performance and satisfied the dispersed suspension criteria. The modified model successfully captured distinct behaviour of the moving-bed layer. Dominant results with previous models results by Ramadan et al. [3] and Cho [4] were achieved.

# Chapter 5

# Conclusion and Recommendation

## 5.1 Conclusion

Based on this work the following can be concluded from the investigation:

1. Preliminary results of the investigation of the particle settling behaviour assured settling behavior increase with increase of the particle size and density combined with regular particle shape, while decrease with increase of fluid density and viscosity.
2. Particle hindered behaviour is as important consideration as dealing with cluster of particles. For the range of the input data, excluding of the cuttings hindered behaviour returned maximum error of 5.6% based on Ham's and hosmy correlation and 3.8% based on Thomas correlation.
3. The mathematically-formulated three-layer model is capable of simulating the behaviour of the horizontal cuttings transport and interpreting the impact of the drilling parameters in an acceptable manner and is in good agreement with what was published in previous works.
4. The two models based on different frictional factors calculations, both captured a thin moving-bed layer at low mud velocities and returned the following two behaviours:

- **First**: By using the Szilas equation, the transport exhibits a similar trend to that observed by Ramadan et al. [3], with continuous growth of the middle moving bed layer in response to increasing annular fluid velocity.
- **Second**: By using other empirical correlations in place of the Szilas et al. equation, the observed moving-bed layer increases with the annular velocity up to a velocity of approximately 1..9 ft/s. It started to diminish with increasing annular velocity and disappeared at annular mud velocity of 3.5 ft/s. This behaviour trend agrees with the findings of Cho [4].

The observed moving-bed behaviours reflected the sensitivity of the mathematical modelling to predict the friction resistance to the flow of the two phases. The second model produced insufficient cuttings transport.

5. Between all examined parameters, the annular mud velocity was the most important variable. Increasing the annular velocity guarantees a better wellbore cleaning and enhances the shear between layers and bed erosion. In general, mud velocity, within range of 3-4 ft/s, is recommended.
6. The cuttings size, fluid viscosity and annular size have a significant impact on the horizontal cuttings transport. Small cuttings size was most easily removed. A bed that consisted of larger sized particles demanded less annular velocity in order to be cleaned.
7. The impact of the cuttings sphericity was realized during analysis of layers concentration. Near to true sphere low concentration was observed in the suspension layer. In spite of the lower influence of the cuttings sphericity on the transport compared to the other tested parameters, approximation of spherical shape for the drilled cuttings returned considerable error in the suspension concentration that reached 27% measured on sphericity of 0.8.
8. The higher the viscosity of the fluid, the more efficient the transport of cuttings would be. This was because it reached the highest suspension thickness at the lower annular velocity.

9. The influence of the operational ROP was lower compared to the whole set of tested parameters. ROP exerted a considerable impact on the total cuttings concentration, whereas high ROP demonstrated higher total concentration.
10. As controllable factor, lower annular size and large drill pipes were the optimal conditions to enhance cuttings removal. Large annulus sizes required application of high annular velocity to achieve cleaning.

### 5.2 Recommendations

On account of the above conclusions, it appears that the study performed requires further improvement. Accordingly, the following recommendations are suggested to achieve a better understanding and analysis of the transportation phenomena:

1. Experimental work is strongly demanded in order to observe the actual behaviour of the moving-bed layer in the annuli. This facilitates the ability to judge whether the behavioural analysis made by Cho [4], and Nugeyn and Rahaman [43], or that reported by Ramadan et al. [3] and Long et al [76], are the most probable.
2. Some modification is essential to compensate lack of the model's to predict the cuttings transfer between two layers which enables detailed follow-up of the layer thicknesses during transport.
3. Involve more length for the well and observe the mud carrying capacity and concentration on the layers.
4. Extend the model to handle more drilling parameters, such as eccentricity, inclination in addition to the influence of the drill-pipe rotation, which immensely affects settling velocity.
5. Modify the solution algorithm to predict the stationary-bed velocity $U_b$ and observe the pressure drop behaviour.
6. Estimate the influence of the down hole pressure and temperature, which affect the fluid density and the properties of mud.

7. Trace the unsteady states situation through the model and inspect the effect of time to present more adequate data about the impact of the ROP on the transport.

Experimental work to observe the cuttings settling and hindered behaviors in non-Newtonian fluids under different particles sphericity

## References

[1] Horizontal drilling - directional oil - gas well - drilling engineering tools Retrieved 6/24/2010, 2010, available: http://www.horizontaldrilling.org/

[2] Cuttings analysis - PanTerra recruitment Retrieved 6/24/2010, 2010, available: http://www.panterra.nl/index.php/cms_categorie/15183/content/categorie/id/15183/CurrentLanguage/.

[3] A. Ramadan, P. Skalle and A. Saasen, "Application of a three-layer modeling approach for solids transport in horizontal and inclined channels," *Chemical Engineering Science*, vol. 60, pp. 2557-2570, 5, 2005.

[4] H. Cho, "Development of a three-segment hydraulic model for cuttings transport in horizontal and deviated wells," Ph.D. dissertation, Graduate Faculty, Univ. of Oklahoma, Norman-Oklahoma pp. 259, 2001.

[5] Welldrilling.pdf (application/pdf object) Retrieved 6/24/2010, 2010, Available: http://www.agwt.org/info/pdfs/welldrilling.pdf.

[6] Drilling and cuttings transport. Retrieved 2/9/2010, 2010, available: www.oilandgas.org.uk/issues/drillcuttings/faq.cfm.

[7] M. N. Belavadi and G. A. Chukwu, "Experimental Study of the Parameters Affecting Cutting Transportation in A vertical Wellbore Annulus," *SPE Paper 27880, presented SPE Western Regional Meeting, 23-25 March 1994*, Long Beach, California, 1994.

[8] T. E. Becker and J. J. Azar, "Mud-Weight and Hole-Geometry Effects on Cuttings Transport While Drilling Directionally," *SPE Paper 14711-MS*, 1985.

[9] H. C. H. Darley and G. R. Gray, "Composition and properties of drilling and completion fluids," in , fifth edition ed.Anonymous USA: Gulf Professional Publishing, 1988, pp. 2-401-466.

[10] S. Joshi, "Horizontal well technology," at Tulsa,Oklahoma-USA: Pennwell Corp, 1991, pp. 1-5.

[11] M. H. Seeberger, R. W. Matlock and P. M. Hanson, "Oil Muds in Large-Diameter, Highly Deviated Wells: Solving the Cuttings Removal Problem," *SPE Paper 18635-MS, presented at SPE/IADC Drilling Conference, 28 February-3 March 1989*, New Orleans, Louisiana, 1989.

[12] A. Ramadan, P. Skalle, S. T. Johansen, J. Svein and A. Saasen, "Mechanistic model for cuttings removal from solid bed in inclined channels," *Journal of Petroleum Science and Engineering*, vol. 30, pp. 129-141, 9, 2001.

[13] R. Chhabra and J. F. Richardson, "Non-newtonian flow in the process industries: Fundamentals and engineering applications," , first edition ed., Great Britain: Butterworth-Heinemann, 1999, pp. 5-7,222.

[14] Oilfield glossary: Term 'thixotropy' Retrieved 6/24/2010, 2010, available: http://www.glossary.oilfield.slb.com/Display.cfm?Term=thixotropy

[15] M. Viloria Ochoa, "Analysis of drilling fluid rheology and tool joint effect to reduce errors in hydraulics calculations," Ph.D. dissertation, Petroleum Eng, Texas ***A&M University,*** Texas pp. 191, 2006.

[16] C. E. Brennen, "Fundamentals of multiphase flow," in , first edition ed. NY-USA: Cambridge Univ Pr, 2005, pp. 21-53,134.

[17] I. C. Walton, "Computer Simulator of Coiled Tubing Wellbore Cleanouts in Deviated Wells Recommends Optimum Pump Rate and Fluid Viscosity," *SPE Paper 29491-MS, presented at SPE Production Operations Symposium, 2-4 April 1995*, Oklahoma City, Oklahoma, 1995.

[18] M. W. Ali, "A parametric study of cutting transport in vertical and horizontal well using computational fluid dynamics (CFD)," M.S. thesis, Dept. of Petroleum and Natural Gas Eng., WVU, Morgantown, West Virginia, pp. 108, 2002.

[19] P. H. Tomren, A. W. Iyoho and J. J. Azar, "Experimental Study of Cuttings Transport in Directional Wells," *SPE Drilling Engineering Paper 12123-PA,* vol. 1, pp. 43-56; 43, 1986.

[20] [20] S. Okrajni and J. J. Azar, "The Effects of Mud Rheology on Annular Hole Cleaning in Directional Wells," *SPE Paper 14178-PA* vol. 1, pp. 297-308, 1986.

[21] N. P. Brown, P. A. Bern and A. Weaver, "Cleaning Deviated Holes: New Experimental and Theoretical Studies," *SPE Paper 18636-MS, presented at SPE/IADC Drilling Conference, 28 February-3 March 1989*, New Orleans, Louisiana, 1989.

[22] J. T. Ford, J. M. Peden, M. B. Oyeneyin, E. Gao and R. Zarrough, "Experimental investigation of drilled cuttings transport in inclined boreholes," *SPE Paper 20421-MS Presented at SPE Annual Technical Conference and Exhibition,* New Orleans, Louisiana, 1990, .

[23] T. R. Sifferman and T. E. Becker, "Hole Cleaning in Full-Scale Inclined Wellbores," *SPE Paper 20422-PA* vol. 7, pp. 115-120, 1992.

[24] A. L. Martins, C. H. M. Sa, A. M. F. Lourenco, L. G. M. Freire and W. Campos, "Experimental Determination of Interfacial Friction Factor in Horizontal Drilling With a Bed of Cuttings," *SPE Paper 36075-MS, presented at SPE Latin America/Caribbean Petroleum Engineering Conference, 23-26 April 1996*, Port-of-Spain, Trinidad, 1996.

[25] J. Li and S. Walker, "Sensitivity Analysis of Hole Cleaning Parameters in Directional Wells," *SPE Paper 54498-MS, presented at SPE/ICoTA Coiled Tubing Roundtable, 25-26 May 1999*, Houston, Texas, 1999.

[26] S. Walker and J. Li, "The Effects of Particle Size, Fluid Rheology, and Pipe Eccentricity on Cuttings Transport," *SPE Paper 60755-MS*, presented at *SPE/ICoTA Coiled Tubing Roundtable, 5-6 April 2000*, Houston, Texas, 2000.

[27] J. Li and S. Walker, "Sensitivity Analysis of Hole Cleaning Parameters in Directional Wells," *SPE Journa Paper 74710-PA* , vol. 6, pp. 356-363; 356, 2001.

[28] Y. Masuda, Q. Doan, M. Oguztoreli, S. Naganawa, T. Yonezawa, A. Kbayashi and A. Kamp, "Critical Cuttings Transport Velocity in Inclined Annulus: Experimental Studies and Numerical Simulation," *SPE Paper 65502-MS*, presented at *SPE/CIM International Conference on Horizontal Well Technology, 6-8 November 2000*, Calgary, Alberta, Canada, 2000.

[29] M. Duan, S. Z. Miska, M. Yu, N. E. Takach, R. M. Ahmed and C. M. Zettner, "Transport of Small Cuttings in Extended Reach Drilling," *SPE Paper 104192-MS, presented at International Oil & Gas Conference and Exhibition in China, 5-7 December 2006,* Beijing, China, 2006.

[30] Forest stand neighbourhood dynamics research and modelling Retrieved 6/24/2010, 2010, available: http://www.bvcentre.ca/sortie-nd/glossary .

[31] R. B. Adari, S. Miska, E. Kuru, P. Bern and A. Saasen, "Selecting Drilling Fluid Properties and Flow Rates For Effective Hole Cleaning in High-Angle and Horizontal Wells," *Paper SPE 63050-MS, presented at SPE Annual Technical Conference and Exhibition, 1-4 October 2000*, Dallas, Texas, 2000 .

[32] R. K. Clark and K. L. Bickham, "A mechanistic model for cuttings transport," *SPE Paper 28306-MS, presented at SPE Annual Technical Conference and Exhibition,* New Orleans, Louisiana, 1994.

[33] W. Campos, "Mechanistic modeling of cuttings transport in directional wells," Ph.D. dissertation, Petroleum Eng., The University of Tulsa, Tulsa, pp. 75, 1995.

[34] L. ZOU, M. H. PATEL and G. HAN, "A new computer package for simulating cuttings transport and predicting hole cleaning in deviated and horizontal wells," SPE *Paper 64646-MS, presented at International Oil and Gas Conference and Exhibition in China,* Beijing, China, 2000, .

[35] A. Ramadan, P. Skalle and S. T. Johansen, "A mechanistic model to determine the critical flow velocity required to initiate the movement of spherical bed particles in inclined channels," *Chemical Engineering Science,* vol. 58, pp. 2153-2163, 5, 2003.

[36] M. Duan, S. Z. Miska, M. Yu, N. E. Takach, R. M. Ahmed and C. M. Zettner, "Critical Conditions for Effective Sand-Sized Solids Transport in Horizontal and High-Angle Wells," *SPE Drilling & Completion paper 106707-PA,* vol. 24, pp. pp. 229-238; pp. 229, 2009.

[37] L. Zhou, "Hole Cleaning During Underbalanced Drilling in Horizontal and Inclined Wellbore," *SPE Drilling & Completion Paper* SPE-98926-PA, vol. 23, pp. pp. 267-273; pp. 267, 2008.

[38] L. Zhou, R. M. Ahmed, S. Z. Miska, N. E. Takach, M. Yu and M. B. Pickell, "Experimental Study and Modeling of Cuttings Transport with Aerated Mud in Horizontal Wellbore at Simulated Downhole Conditions," *SPE Paper 90038-MS, presented at SPE Annual Technical Conference and Exhibition, 26-29 September 2004*, Houston, Texas, 2004.

[39] A. M. Kamp and M. Rivero, "Layer modeling for cuttings transport in highly inclined wellbores," *SPE Paper 53942-MS, presented at Latin American and Caribbean Petroleum Engineering Conference,* Caracas, Venezuela, 1999, .

[40] A. A. Gavignet and I. J. Sobey, "Model Aids Cuttings Transport Prediction," *SPE Journal of Petroleum Technology Paper 15417-PA*, vol. 41, pp. 916-921; 916, 1989.

[41] A. W. Iyoho, "Drilled-Cuttings Transport by Non-Newtonian Drilling Fluids through Inclined, Eccentric Annuli," Ph.D. dissertation, U of Tulsa, Tulsa, pp. 282, 1980.

[42] A. L. Martins and C. C. Santana, "Evaluation of Cuttings Transport in Horizontal and Near Horizontal Wells -A Dimensionless Approach," *SPE Paper 23643-MS, presented at SPE Latin America Petroleum Engineering Conference, 8-11 March 1992*, Caracas, Venezuela, 1992.

[43] [43] D. Nguyen and S. S. Rahman, "A three-layer hydraulic program for effective cuttings transport and hole cleaning in highly deviated and horizontal wells," *SPE Paper 36383-MS presented at SPE/IADC Asia Pacific Drilling Technology,* Kuala Lumpur, Malaysia, 1996, .

[44] D. Nguyen and S. S. Rahman, "A Three-Layer Hydraulic Program for Effective Cuttings Transport and Hole Cleaning in Highly Deviated and Horizontal Wells," *SPE Drilling & Completion SPE Paper 51186-PA, vol*. 13, pp. 182-189; 182, 1998.

[45] Z. G. Feng and E. Michaelides, "Proteus—A new computational scheme for deformable particles and particle interaction problems," *presented at IUTAM Symposium on Computational Approaches to Multiphase Flow,* 2006, pp. 153-161.

[46] M. Santana, A. L. Martins and A. Sales Jr, "Advances in the modeling of the stratified flow of drilled cuttings in high horizontal wells," in *SPE Paper 39890-MS Presented at International Petroleum Conference and Exhibition of Mexico,* Villahermosa, Mexico, 1998, .

[47] P. Stevenson, "Comments on "Application of a three-layer modelling approach for solids transport in horizontal and inclined channels": A. Ramadan, P. Skalle, A. Saasen [Chemical Engineering Science 2005, 60, 2557–2570]," *Chemical Engineering Science,* vol. 61, pp. 3791-3791, 6, 2006.

[48] A. Ramadan, "Response to comments on: "Application of a three-layer modeling approach for solids transportation in horizontal and inclined channels" by A. Ramadan, P. Skalle, and A. Saasen," *Chemical Engineering Science,* vol. 61, pp. 3792-3793, 6, 2006.

[49] W. C. Yang, "Particle Characterization and Dynamics," *Handbook of Fluidization and Fluid-Particle Systems,* pp. 1, 2003.

[50] [50] S. Chien, "Settling Velocity of Irregularly Shaped Particles," *SPE Paper 26121-PA,* vol. 9, pp. 281-289, 1994.

[51] Q. T. Doan, M. Oguztoreli, Y. Masuda, T. Yonezawa, A. Kobayashi, S. Naganawa and A. Kamp, "Modeling of Transient Cuttings Transport in Underbalanced Drilling (UBD)," *SPE Journa Paper 85061-PA,l, vol.* 8, pp. 160-170; 160, 2003.

[52] S. Naganawa and T. Nomura, "Simulating Transient Behavior of Cuttings Transport over Whole Trajectory of Extended Reach Well," *SPE Paper 103923-MS, presented at IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, 13-15 November 2006*, Bangkok, Thailand, 2006.

[53] S. S. Costa, S. Stuckenbruck, S. A. B. Fontoura and A. L. Martins, "Simulation of transient cuttings transportation and ECD in wellbore drilling," *SPE 113893-MS*, presented at *Europec/EAGE Conference and Exhibition,* Rome, Italy, 2008, .

[54] R. CHENG and R. WANG, "A Three-Segment Hydraulic Model for Annular Cuttings Transport With Foam in Horizontal Drilling," *Journal of Hydrodynamics, Ser.B*, vol. 20, pp. 67-73, 2, 2008.

[55] J. Capo, M. Yu, S. Z. Miska, N. Takach and R. Ahmed, "Cuttings Transport with Aqueous Foam at Intermediate Inclined Wells," *SPE Paper 89534-MS, presented at SPE/ICoTA Coiled Tubing Conference and Exhibition, 23-24 March 2004,* Houston, Texas, 2004.

[56] N. Mishra, "Investigation of hole cleaning parameters using computational fluid dynamics in horizontal and deviated wells," M.S. thesis, Dept. of Petroleum and Natural Gas Eng., WVU, Morgantown, West Virginia, pp. 75, 2007.

[57] H. Massah, L. Oshinowo, F. Incorporated and N. H. Lebanon, "Advanced Gas-Solid Multiphase Flow Models Offer Significant Process Improvements," *Journal Articles by Fluent Software Users,* pp. 1–6, 2000.

[58] A. L. Martins, C. H. M. Sa, A. M. F. Lourenco and W. Campos, "Optimizing Cuttings Circulation In Horizontal Well Drilling," *SPE Paper 35341-MS, presented at International Petroleum Conference and Exhibition of Mexico, 5-7 March 1996*, Villahermosa, Mexico, 1996.

[59] J. Brill and H. Mukherjee, "Multiphase flow in wells," in , first edition ed., SPE, Texas: Richardson, 1999, pp. 5-6.

[60] CHEE2940 lecture 8 - multiple particle settling Retrieved 6/24/2010, 2010, available: http://www.scribd.com/doc/7213729/CHEE2940-Lecture-8-Multiple-Particle-Settling .

[61] G. Haagh and V. D. Vosse, "Simulation of three-dimensional polymer mould filling processes using a pseudo-concentration method," *International Journals for Numrical Methods in Fluids,* vol. 28, pp. 1355-1369, 1998.

[62] R. Bagnold, "Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear," *Proceedings of the Royal Society of London.Series A, Mathematical and Physical Sciences,* vol. 225, pp. 49-63, 1954.

[63] J. Freds√∏e and R. Deigaard, "Mechanics of coastal sediment transport," in , firist edition ed., London, Singapore: World Scientific Pub Co Inc, 1992, pp. 219-220,222.

[64] J. Ham and G. Homsy, "Hindered settling and hydrodynamic dispersion in quiescent sedimenting suspensions," *International Journal of Multiphase Flow,* vol. 14, pp. 533-546, 1988.

[65] H. Cho, S. N. Shah and S. O. Osisanya, "A three-layer modeling for cuttings transport with coiled tubing horizontal drilling," *SPE Paper 63269-MS,* presented at *SPE Annual Technical Conference and Exhibition,* Dallas, Texas, 2000, .

[66] J. Li and G. Wilde, "Effect of Particle Density and Size on Solids Transport and Hole Cleaning With Coiled Tubing," *SPE Paper 94187-MS, presented at SPE/ICoTA Coiled Tubing Conference and Exhibition, 12-13 April 2005,* The Woodlands, Texas, 2005.

[67] M. Zamora, D. T. Jefferson and J. W. Powell, "Hole-Cleaning Study of Polymer-Based Drilling Fluids," *SPE Paper 26329-MS, presented at SPE Annual Technical Conference and Exhibition, 3-6 October 1993,* Houston, Texas, 1993.

[68] Y. Zhou and S. N. Shah, "Rheological Properties and Frictional Pressure Loss of Drilling, Completion, and Stimulation Fluids in Coiled Tubing " *Journal of Fluids Engineering,* vol. 126, pp. 153, 2004.

[69] M. E. Ozbayoglu, S. Z. Miska, T. Reed and N. Takach, "Analysis of the Effects of Major Drilling Parameters on Cuttings Transport Efficiency for High-Angle Wells in Coiled Tubing Drilling Operations," *SPE Paper 89334-MS, presented at SPE/ICoTA Coiled Tubing Conference and Exhibition, 23-24 March 2004*, Houston, Texas, 2004.

[70] A. Altunbas, G. Kelbaliyev and K. Ceylan, "Eddy diffusivity of particles in turbulent flow in rough channels," *J. Aerosol Sci.,* vol. 33, pp. 1075-1086, 7, 2002.

[71] M. Duan, S. Z. Miska, M. Yu, N. E. Takach, R. M. Ahmed and J. H. Hallman, "Experimental Study and Modeling of Cuttings Transport Using Foam With Drillpipe Rotation," *SPE Paper 116300-MS, presented at SPE Annual Technical Conference and Exhibition, 21-24 September 2008,* Denver, Colorado, USA, 2008.

[72] A. Saasen and G. L√∏klingholm, "The Effect of Drilling Fluid Rheological Properties on Hole Cleaning," *SPE Paper 74558-MS, presented at IADC/SPE Drilling Conference, 26-28 February 2002*, Dallas, Texas, 2002.

[73] K. Shahbazi, M. R. Meschi and M. P. Shahri, "A New Criteria to Predict Stuck Pipe Occurrence," *SPE Paper 128376-MS, presented at North Africa Technical Conference and Exhibition, 14-17 February 2010,* Cairo, Egypt, 2010.

[74] J. J. Azar and R. A. Sanchez, "Important Issues in Cuttings Transport for Drilling Directional Wells," *SPE Paper 39020-MS, Latin American and Caribbean Petroleum Engineering Conference, 30 August-3 September 1997*, Rio de Janeiro, Brazil, 1997.

[75] P. S. Vinod and L. V. McIntire, "Rheology Effects on Laminar and Turbulent Flow of Model Drilling Fluids Through Deviated Wells," , *SPE Paper 28287-MS*, 1994. "Unsolicited"

[76] Z. Long, Z. Wang and X. Guo, "Transport mechanism of cuttings in annulus during deviated and horizontal drilling," *Journals of University of Petroulim,* Chaina, vol. 29, pp. 42-45, 2005.

# Appendix A

## Geometry Engine

(1) If $TT=(r_w-r_p)$ or $<(r_w-r_p)$ $(r_w=D_w/2\ ,\ r_p=D_p/2)$

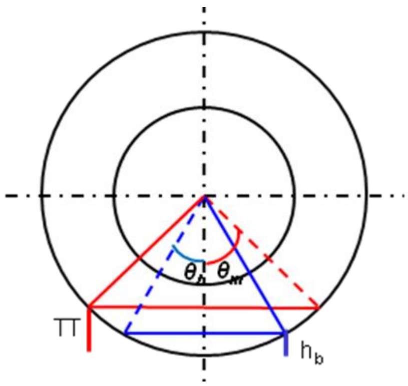


Figure A-1: The Bed Layers below the Drill-Pipe

<u>Angles</u>

$$\theta_b = \cos^{-1}\left(\frac{r_w - h_b}{r_w}\right) \quad \theta_m = \cos^{-1}\left(\frac{r_w - TT}{r_w}\right)$$

<u>Areas</u>

$$A_b = r_w^2\left[(\theta_b) - (\sin\theta_b)(\cos\theta_b)\right]$$

$$A_m = r_w^2\left[(\theta_m) - \sin\theta_m\cos\theta_m - (\theta_b) + \sin\theta_b\cos\theta_b\right]$$

$$A_s = A_a - A_m - A_b$$

Perimeters

$$S_{bw} = 2r_w\theta_b = D_w\theta_b$$

$$S_{mb} = 2r_w \sin\theta_b$$

$$S_{sm} = 2r_w \sin\theta_m$$

$$S_{mw} = 2r_w(\theta_m - \theta_b)$$

$$S_{sw} = S_{well} - S_{mw} - S_{bw} + S_{pipe}$$

$$S_{sw} = 2\pi r_w - 2r_w(\theta_m - \theta_b) - 2r_w\theta_{bS} + S_{pipe}$$

$$S_{sw} = 2r_w(\pi - \theta_m) + 2\pi r_p$$

Hydraulic diameter

$$D_{hs} = \frac{4A_s}{S_p + S_{sw} + S_{sm}}$$

(2) If TT>(rw-rb)

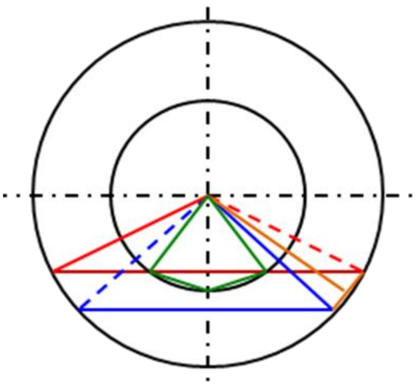

Figure A-2: The Bed Layers reach the Drill-Pipe

Areas

$$A_b = r_w^2\left[(\theta_b) - (\sin\theta_b \cos\theta_b)\right]$$

$$A_m = r_w^2(\sin\theta_m + \sin\theta_m)(\cos\theta_b - \cos\theta_m) + \left[r_w^2(\theta_m - \theta_b)\right] -$$
$$\left[\sqrt{(r_w(\cos\theta_b - \cos\theta_m))^2 + r_w^2(\sin\theta_m - \sin\theta_b)^2} \cdot \sqrt{r_w^2 - \frac{1}{4}\sqrt{t^2 + r_w^2(\sin\theta_m - \sin\theta_b)^2}}\right] -$$
$$\left(\left[r_p^2\left(\cos^{-1}\left[\frac{r_w \cos\theta_m}{r_p}\right]\right)\right] - \left[r_w \cos\theta_m \cdot \sqrt{r_p^2 - r_w^2 \cos^2\theta_m}\right]\right)$$

$$A_s = A_a - A_b - A_m$$

Perimeters

$$S_{bw} = 2r_w\theta_b$$

$$S_{mb} = 2r_w \sin\theta_b$$

$$S_{mw} = 2r_w(\theta_m - \theta_b) + 2r_p \cos^{-1}\frac{r_w \cos\theta_m}{r_p}$$

$$S_{sm} = 2\left[r_w \sin\theta_m - r_p \sin\left(\cos^{-1}\frac{r_w \cos\theta_m}{r_p}\right)\right]$$

$$S_{sw} = 2r_w(\pi - \theta_m) + 2r_p\left(\pi - \cos^{-1}\frac{r_w \cos\theta_m}{r_p}\right)$$

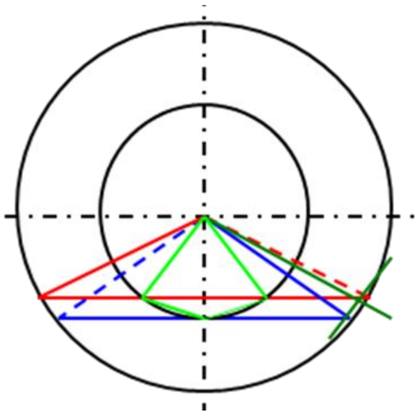

Figure A-3: The Bed Layers touch the Drill-Pipe

Areas

$$A_b = r_w^2\left[(\theta_b) - (\sin\theta_b)(\cos\theta_b)\right]$$

$$A_m = r_w^2(\sin\theta_m + \sin\theta_m)(\cos\theta_b - \cos\theta_m) + \left[r_w^2(\theta_m - \theta_b)\right] -$$
$$\left[\sqrt{\left(r_w(\cos\theta_b - \cos\theta_m)\right)^2 + r_w^2(\sin\theta_m - \sin\theta_b)^2}\,.\sqrt{r_w^2 - \frac{1}{4}\sqrt{t^2 + r_w^2(\sin\theta_m - \sin\theta_b)^2}}\right]$$
$$-\left(\left[r_p^2\left(\cos^{-1}\left[\frac{r_w\cos\theta_m}{r_p}\right]\right)\right] - \left[r_w\cos\theta_m\sqrt{r_p^2 - r_w^2(\cos\theta_m)^2}\,.\right]\right)$$

$$A_s = A_a - A_b - A_m$$

Perimeters

$$S_{bw} = 2r_w\theta_b$$

$$S_{mb} = 2r_w\sin\theta_b$$

$$S_{mw} = 2r_w(\theta_m - \theta_b) + 2r_p\cos^{-1}\frac{r_w\cos\theta_m}{r_p}$$

$$S_{sm} = 2\left[ r_w \sin\theta_m - r_p \sin\left( \cos^{-1} \frac{r_w \cos\theta_m}{r_p} \right)\right]$$

$$S_{sw} = 2r_w(\pi - \theta_m) + 2r_p\left( \pi - \cos^{-1} \frac{r_w \cos\theta_m}{r_p} \right)$$

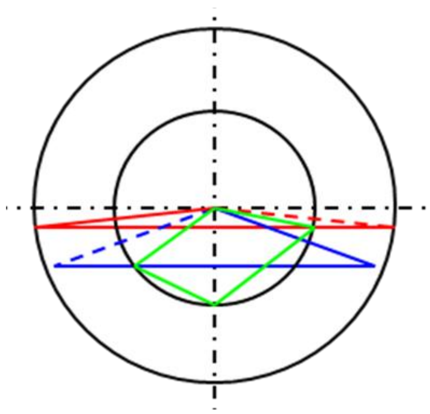

Figure A-4: The Bed Layers over the Drill-Pipe

<u>Areas</u>

$$A_b = \left(r_w^2 \theta_b\right) - \left(r_w^2 \cos\theta_b \sin\theta_b\right) - r_p^2\left( \cos^{-1}\left[ \frac{r_w \cos\theta_b}{r_p} \right]\right) + \left[ r_w \cos\theta_b \sqrt{r_p^2 - r_w^2 \cos^2\theta_b} \right]$$

$$A_m = \left(r_w^2 (\sin\theta_m - \sin\theta_b)(\cos\theta_b - \cos\theta_m)\right) - \left(r_w^2 \theta_m\right) - \left(r_w^2 \sin\theta_m \cos\theta_m\right) -$$
$$\left( r_p^2 \cos^{-1}\left( \frac{r_w}{r_p} \cos\theta_m \right)\right) + \left( r_w \cos\theta_m \sqrt{r_p^2 - r_w^2 \cos\theta_m} \right) - \left[ r_p^2 \left( \cos^{-1}\left[ \frac{r_w \cos\theta_b}{r_p} \right]\right)\right]$$
$$+ \left( r_w \cos\theta_b \sqrt{r_p^2 - r_w^2 \cos^2\theta_b} \right)$$

$$A_s = A_a - A_b - A_m$$

Perimeters

$$S_{sw} = 2r_w(\pi - \theta_m) + 2r_p\left(\pi - \cos^{-1}\frac{r_w \cos\theta_m}{r_p}\right)$$

$$S_{mw} = 2r_w(\theta_m - \theta_b) + 2r_p\left(\cos^{-1}\frac{r_w \cos\theta_m}{r_p} - \cos^{-1}\frac{r_w \cos\theta_b}{r_p}\right)$$

$$S_{bw} = 2r_w\theta_b - 2r_p \cos^{-1}\frac{r_w \cos\theta_b}{r_p}$$

$$S_{sm} = 2\left[r_w \sin\theta_m - r_p \sin\left(\cos^{-1}\frac{r_w \cos\theta_m}{r_p}\right)\right]$$

$$S_{mb} = 2\left[r_w \sin\theta_b - r_p \sin\left(\cos^{-1}\frac{r_w \cos\theta_b}{r_p}\right)\right]$$

## Appendix B

# Results of the Basic Simulation

**Results of the cuttings sizes:**

Table B-1: Large size of 0.25 in

| Large Cuttings Size $d_p$ = 0.25 in | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $U_a$ (ft/s) | $Re_s$ | $U_s$ (ft/s) | $U_m$ (ft/s) | $c_s$ | $c_m$ | $t_m$ (in) | $\tau_{dis}$ (lb/ft$^2$) | dpz /dz (psi/ft) |
| 0.75 | 5806 | 0.9676 | 0.3686 | 0.006 | 0.253 | 0.0072 | 0.6709 | 0.118059 |
| 1 | 8427 | 1.2973 | 0.4795 | 0.008 | 0.254 | 0.0132 | 1.2185 | 0.194837 |
| 2 | 20809 | 2.6161 | 0.9145 | 0.0158 | 0.2579 | 0.0552 | 5.2793 | 0.683883 |
| 3 | 35407 | 3.9348 | 1.3459 | 0.0245 | 0.2623 | 0.1428 | 13.6283 | 1.47371 |
| 4 | 51666 | 5.2535 | 1.7768 | 0.0343 | 0.2671 | 0.3252 | 31.0298 | 2.579816 |
| 4.7 | 63870 | 6.1766 | 2.0785 | 0.0418 | 0.2709 | 0.666 | 63.4897 | 3.552158 |

Table B-2: Medium size of 0.175 in

| $U_a$ (ft/s) | $Re_s$ | $U_s$ (ft/s) | $U_m$ (ft/s) | $c_s$ | $c_m$ | $t_m$ (in) | $\tau_{dis}$ ($lb/ft^2$) | dpz /dz (psi/ft) |
|---|---|---|---|---|---|---|---|---|
| **Medium Cuttings Size $d_p$ = 0.175 in** | | | | | | | | |
| 0.75 | 5806 | 0.9676 | 0.3602 | 0.008 | 0.254 | 0.0072 | 0.6548 | 0.110635 |
| 1 | 8427 | 1.2973 | 0.4664 | 0.0105 | 0.2552 | 0.012 | 1.1787 | 0.180722 |
| 2 | 20809 | 2.6161 | 0.8795 | 0.0211 | 0.2605 | 0.0528 | 4.9793 | 0.618289 |
| 3 | 35407 | 3.9348 | 1.2859 | 0.033 | 0.2665 | 0.132 | 12.5598 | 1.315999 |
| 4 | 51666 | 5.2535 | 1.6907 | 0.047 | 0.2735 | 0.288 | 27.4821 | 2.292176 |
| 4.7 | 63870 | 6.1766 | 1.9738 | 0.0581 | 0.279 | 0.5232 | 49.8867 | 3.153541 |
| 4.9 | 67468 | 6.4404 | 2.0546 | 0.0614 | 0.2807 | 0.6636 | 63.2615 | 3.427962 |

Table B-3: small size of 0.76 mm

| $U_a$ (ft/s) | $Re_s$ | $U_s$ (ft/s) | $U_m$ (ft/s) | $c_s$ | $c_m$ | $t_m$ (in) | $\tau_{dis}$ ($lb/ft^2$) | dpz /dz (psi/ft) |
|---|---|---|---|---|---|---|---|---|
| **Small Cuttings Size $d_p$ = 0.76 mm** | | | | | | | | |
| 0.75 | 5806 | 0.9676 | 0.3431 | 0.1727 | 0.3363 | 0.0084 | 0.8014 | 0.117953 |
| 1 | 8427 | 1.2973 | 0.4396 | 0.2172 | 0.3586 | 0.0156 | 1.4746 | 0.196229 |
| 2 | 20809 | 2.6161 | 0.8016 | 0.2977 | 0.3988 | 0.0648 | 6.1829 | 0.660774 |
| 3 | 35407 | 3.9348 | 1.1437 | 0.3335 | 0.4168 | 0.1572 | 15.0127 | 1.348795 |
| 4 | 51666 | 5.2535 | 1.4756 | 0.3558 | 0.4279 | 0.3252 | 31.06 | 2.249014 |
| 4.7 | 63870 | 6.1766 | 1.7041 | 0.3674 | 0.4337 | 0.5496 | 52.3887 | 3.002478 |
| 4.9 | 67468 | 6.4404 | 1.7689 | 0.3702 | 0.4351 | 0.6588 | 62.853 | 3.236164 |
| 5 | 69285 | 6.5723 | 1.8013 | 0.3716 | 0.4358 | 0.7392 | 70.5393 | 3.356149 |

**Results of the cuttings sphericity:**

Table B-4: Cuttings sphericity of 0.75

| $\varphi$= 0.75 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $U_a$ (ft/s) | Re | $U_s$ (ft/s) | $U_m$ (ft/s) | $c_s$ | $c_m$ | $t_m$ (in) | $\tau_{dis}$ (lb/ft$^2$) | dpz /dz (psi/ft) |
| 0.75 | 5806 | 0.9676 | 0.3686 | 0.0065 | 0.2533 | 0.0072 | 0.6715 | 0.118139 |
| 1 | 8427 | 1.2973 | 0.4795 | 0.0086 | 0.2543 | 0.0132 | 1.2199 | 0.195014 |
| 2 | 20809 | 2.6161 | 0.9145 | 0.0172 | 0.2586 | 0.0552 | 5.2922 | 0.685181 |
| 3 | 35407 | 3.9348 | 1.3459 | 0.0269 | 0.2634 | 0.144 | 13.6879 | 1.478269 |
| 4 | 51666 | 5.2535 | 1.7768 | 0.0378 | 0.2689 | 0.3276 | 31.2884 | 2.591944 |
| 4.7 | 63870 | 6.1766 | 2.0785 | 0.0464 | 0.2732 | 0.6816 | 65.0048 | 3.573254 |

Table B-5: Cuttings sphericity of 0.8

| $\varphi$= 0.8 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $U_a$ (ft/s) | Re | $U_s$ (ft/s) | $U_m$ (ft/s) | $c_s$ | $c_m$ | $t_m$ (in) | $\tau_{dis}$ (lb/ft$^2$) | dpz /dz (psi/ft) |
| 0.75 | 5806 | 0.9676 | 0.3686 | 0.006 | 0.253 | 0.0072 | 0.6709 | 0.118059 |
| 1 | 8427 | 1.2973 | 0.4795 | 0.008 | 0.254 | 0.0132 | 1.2185 | 0.194837 |
| 2 | 20809 | 2.6161 | 0.9145 | 0.0158 | 0.2579 | 0.0552 | 5.2793 | 0.683883 |
| 3 | 35407 | 3.9348 | 1.3459 | 0.0245 | 0.2623 | 0.1428 | 13.6283 | 1.47371 |
| 4 | 51666 | 5.2535 | 1.7768 | 0.0343 | 0.2671 | 0.3252 | 31.0298 | 2.579816 |
| 4.7 | 63870 | 6.1766 | 2.0785 | 0.0418 | 0.2709 | 0.666 | 63.4897 | 3.552158 |

Table B-6: Cuttings sphericity of 0.85

| $\varphi$= 0.85 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $U_a$ (ft/s) | Re | $U_s$ (ft/s) | $U_m$ (ft/s) | $c_s$ | $c_m$ | $t_m$ (in) | $\tau_{dis}$ ($lb/ft^2$) | dpz /dz (psi/ft) |
| 0.75 | 5806 | 0.9676 | 0.3686 | 0.0056 | 0.2528 | 0.0072 | 0.6701 | 0.11799 |
| 1 | 8427 | 1.2973 | 0.4795 | 0.0073 | 0.2537 | 0.0132 | 1.2171 | 0.194665 |
| 2 | 20809 | 2.6161 | 0.9145 | 0.0146 | 0.2573 | 0.0552 | 5.2682 | 0.682767 |
| 3 | 35407 | 3.9348 | 1.3459 | 0.0226 | 0.2613 | 0.1428 | 13.5742 | 1.469831 |
| 4 | 51666 | 5.2535 | 1.7768 | 0.0313 | 0.2657 | 0.3228 | 30.8106 | 2.569898 |
| 4.7 | 63870 | 6.1766 | 2.0785 | 0.0381 | 0.2691 | 0.654 | 62.3175 | 3.53493 |

Table B-7: Cuttings sphericity of 0.9

| $\varphi$ = 0.9 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $U_a$ (ft/s) | Re | $U_s$ (ft/s) | $U_m$ (ft/s) | $c_s$ | $c_m$ | $t_m$ (in) | $\tau_{dis}$ ($lb/ft^2$) | dpz /dz (psi/ft) |
| 0.75 | 5806 | 0.9676 | 0.3686 | 0.0052 | 0.2526 | 0.0072 | 0.6697 | 0.117923 |
| 1 | 8427 | 1.2973 | 0.4795 | 0.0068 | 0.2534 | 0.0132 | 1.216 | 0.194534 |
| 2 | 20809 | 2.6161 | 0.9145 | 0.0136 | 0.2568 | 0.0552 | 5.2586 | 0.68181 |
| 3 | 35407 | 3.9348 | 1.3459 | 0.0209 | 0.2604 | 0.1416 | 13.5312 | 1.466531 |
| 4 | 51666 | 5.2535 | 1.7768 | 0.0289 | 0.2644 | 0.3216 | 30.6341 | 2.561542 |
| 4.7 | 63870 | 6.1766 | 2.0785 | 0.0349 | 0.2675 | 0.6432 | 61.3912 | 3.520121 |

Table B-8: Cuttings sphericity of 0.95

| $\varphi$= 0.95 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $U_a$ (ft/s) | Re | $U_s$ (ft/s) | $U_m$ (ft/s) | $c_s$ | $c_m$ | $t_m$ (in) | $\tau_{dis}$ (lb/ft$^2$) | dpz /dz (psi/ft) |
| 0.75 | 5806 | 0.9676 | 0.3686 | 0.0049 | 0.2524 | 0.0072 | 0.6693 | 0.117878 |
| 1 | 8427 | 1.2973 | 0.4795 | 0.0064 | 0.2532 | 0.0132 | 1.2151 | 0.194422 |
| 2 | 20809 | 2.6161 | 0.9145 | 0.0126 | 0.2563 | 0.0552 | 5.2498 | 0.680921 |
| 3 | 35407 | 3.9348 | 1.3459 | 0.0194 | 0.2597 | 0.1416 | 13.4928 | 1.463571 |
| 4 | 51666 | 5.2535 | 1.7768 | 0.0267 | 0.2634 | 0.3192 | 30.4804 | 2.554227 |
| 4.7 | 63870 | 6.1766 | 2.0785 | 0.0323 | 0.2662 | 0.636 | 60.6183 | 3.508105 |
| 4.8 | 65663 | 6.3085 | 2.1216 | 0.0331 | 0.2666 | 0.7908 | 75.4277 | 3.657458 |

Table B-9: Cuttings sphericity of 1

| $\varphi$= 1 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $U_a$ (ft/s) | Re | $U_s$ (ft/s) | $U_m$ (ft/s) | $c_s$ | $c_m$ | $t_m$ (in) | $\tau_{dis}$ (lb/ft$^2$) | dpz /dz (psi/ft) |
| 0.75 | 5806 | 0.9676 | 0.3686 | 0.0046 | 0.2523 | 0.0072 | 0.6689 | 0.117833 |
| 1 | 8427 | 1.2973 | 0.4795 | 0.006 | 0.253 | 0.0132 | 1.2143 | 0.194325 |
| 2 | 20809 | 2.6161 | 0.9145 | 0.0119 | 0.2559 | 0.0552 | 5.2429 | 0.680228 |
| 3 | 35407 | 3.9348 | 1.3459 | 0.0182 | 0.2591 | 0.1416 | 13.4621 | 1.461211 |
| 4 | 51666 | 5.2535 | 1.7768 | 0.025 | 0.2625 | 0.318 | 30.3568 | 2.548336 |
| 4.7 | 63870 | 6.1766 | 2.0785 | 0.0301 | 0.2651 | 0.63 | 60.0517 | 3.498042 |
| 4.8 | 65663 | 6.3085 | 2.1216 | 0.0309 | 0.2655 | 0.7668 | 73.1604 | 3.646662 |

**Results of the fluid Viscosity:**

Table B-10: power law viscosity at K=0.00084 lbf.sn/ft2; n=0.68

| K=0.00084 $lb_f.s^n/ft^2$; n=0.68 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $U_a$ (ft/s) | Re | $U_s$ (ft/s) | $U_m$ (ft/s) | $c_s$ | $c_m$ | $t_m$ (in) | $\tau_{dis}$ ($lb/ft^2$) | dpz /dz (psi/ft) |
| 0.75 | 41474 | 0.9676 | 0.3298 | 0.0054 | 0.2527 | 0.0072 | 0.6452 | 0.085967 |
| 1 | 60192 | 1.2973 | 0.4375 | 0.0072 | 0.2536 | 0.012 | 1.1673 | 0.150498 |
| 2 | 148640 | 2.6161 | 0.8689 | 0.015 | 0.2575 | 0.0528 | 5.091 | 0.593387 |
| 3 | 252910 | 3.9348 | 1.301 | 0.0236 | 0.2618 | 0.138 | 13.1498 | 1.341215 |
| 4 | 369040 | 5.2535 | 1.7334 | 0.0332 | 0.2666 | 0.3108 | 29.6483 | 2.407873 |
| 4.6 | 443490 | 6.0447 | 1.9929 | 0.0397 | 0.2698 | 0.5364 | 51.1194 | 3.207971 |
| 4.7 | 456210 | 6.1766 | 2.0361 | 0.0408 | 0.2604 | 0.6036 | 57.5205 | 3.353336 |
| 4.8 | 469020 | 6.3085 | 2.0794 | 0.0419 | 0.2709 | 0.7032 | 67.0779 | 3.502144 |

Table B-11: power law viscosity at K=0.006 lbf.sn/ft2; n=0.68

| K=0.006 $lb_f.s^n/ft^2$; n=0.68 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $U_a$ (ft/s) | Re | $U_s$ (ft/s) | $U_m$ (ft/s) | $c_s$ | $c_m$ | $t_m$ (in) | $\tau_{dis}$ ($lb/ft^2$) | dpz /dz (psi/ft) |
| 0.75 | 5806 | 0.9676 | 0.3686 | 0.006 | 0.253 | 0.0072 | 0.6709 | 0.118059 |
| 1 | 8427 | 1.2973 | 0.4795 | 0.008 | 0.254 | 0.0132 | 1.2185 | 0.194837 |
| 2 | 20809 | 2.6161 | 0.9145 | 0.0158 | 0.2579 | 0.0552 | 5.2793 | 0.683883 |
| 3 | 35407 | 3.9348 | 1.3459 | 0.0245 | 0.2623 | 0.1428 | 13.6283 | 1.47371 |
| 4 | 51666 | 5.2535 | 1.7768 | 0.0343 | 0.2671 | 0.3252 | 31.0298 | 2.579816 |
| 4.6 | 62088 | 6.0447 | 2.0354 | 0.0407 | 0.2704 | 0.5784 | 55.1324 | 3.403004 |
| 4.7 | 63870 | 6.1766 | 2.0785 | 0.0418 | 0.2709 | 0.666 | 63.4897 | 3.552158 |

Table B-12: power law viscosity at K=0.00436 lbf.sn/ft2; n=0.61

| K=0.00436 $lb_f.s^n/ft^2$; n=0.61 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $U_a$ (ft/s) | Re | $U_s$ (ft/s) | $U_m$ (ft/s) | $c_s$ | $c_m$ | $t_m$ (in) | $\tau_{dis}$ ($lb/ft^2$) | dpz /dz (psi/ft) |
| 0.75 | 9811 | 0.9676 | 0.3763 | 0.0054 | 0.2527 | 0.0072 | 0.6669 | 0.125305 |
| 1 | 14530 | 1.2973 | 0.4881 | 0.007 | 0.2535 | 0.0132 | 1.2175 | 0.204933 |
| 2 | 37662 | 2.6161 | 0.9246 | 0.014 | 0.257 | 0.0552 | 5.2869 | 0.703474 |
| 3 | 65928 | 3.9348 | 1.3558 | 0.0214 | 0.2607 | 0.1428 | 13.6172 | 1.49768 |
| 4 | 98160 | 5.2535 | 1.7861 | 0.0296 | 0.2648 | 0.324 | 30.9066 | 2.601093 |
| 4.6 | 119120 | 6.0447 | 2.0443 | 0.0349 | 0.2674 | 0.5736 | 54.6635 | 3.417617 |
| 4.7 | 122720 | 6.1766 | 2.0873 | 0.0358 | 0.2679 | 0.6576 | 62.708 | 3.565325 |

Table B-13: power law viscosity at K=0.0093 lbf.sn/ft2; n=0.61

| K=0.0093 $lb_f.s^n/ft^2$; n=0.61 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $U_a$ (ft/s) | Re | $U_s$ (ft/s) | $U_m$ (ft/s) | $c_s$ | $c_m$ | $t_m$ (in) | $\tau_{dis}$ ($lb/ft^2$) | dpz /dz (psi/ft) |
| 0.75 | 4600 | 0.9676 | 0.4035 | 0.0058 | 0.2529 | 0.0072 | 0.6378 | 0.155058 |
| 1 | 6812 | 1.2973 | 0.5204 | 0.0075 | 0.2538 | 0.0132 | 1.2072 | 0.24791 |
| 2 | 17657 | 2.616 | 0.9687 | 0.0147 | 0.2574 | 0.0552 | 5.4453 | 0.803913 |
| 3 | 30908 | 3.9348 | 1.4051 | 0.0223 | 0.2612 | 0.1428 | 14.2144 | 1.656788 |
| 4 | 46019 | 5.2535 | 1.8375 | 0.0306 | 0.2653 | 0.324 | 32.8565 | 2.817549 |
| 4.6 | 55846 | 6.0447 | 2.0962 | 0.036 | 0.268 | 0.5736 | 61.6358 | 3.667771 |

**Results of the Rate of penetration:**

Table B-14: ROP at 60 ft/r

| 60 ft/r | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **$U_a$ (ft/s)** | **Re** | **$U_s$ (ft/s)** | **$U_m$ (ft/s)** | **$c_s$** | **$c_m$** | **$t_m$ (in)** | **$\tau_{dis}$ ($lb/ft^2$)** | **dpz /dz (psi/ft)** |
| 0.75 | 5840 | 0.9634 | 0.3672 | 0.006 | 0.253 | 0.0072 | 0.6647 | 0.117181 |
| 1 | 8464 | 1.293 | 0.478 | 0.0078 | 0.2539 | 0.0132 | 1.2102 | 0.193703 |
| 2 | 20855 | 2.6118 | 0.9131 | 0.0158 | 0.2579 | 0.0552 | 5.2613 | 0.681822 |
| 3 | 35459 | 3.9305 | 1.3445 | 0.0245 | 0.2623 | 0.1428 | 13.5887 | 1.470645 |
| 4 | 51723 | 5.2492 | 1.7754 | 0.0342 | 0.2671 | 0.324 | 30.9474 | 2.575701 |
| 4.7 | 63930 | 6.1723 | 2.0771 | 0.0418 | 0.2609 | 0.6624 | 63.1676 | 3.547292 |

Table B-15: ROP at 50 ft/r

| 50 ft/r | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **$U_a$ (ft/s)** | **Re** | **$U_s$ (ft/s)** | **$U_m$ (ft/s)** | **$c_s$** | **$c_m$** | **$t_m$ (in)** | **$\tau_{dis}$ ($lb/ft^2$)** | **dpz /dz (psi/ft)** |
| 0.75 | 5806 | 0.9676 | 0.3686 | 0.006 | 0.253 | 0.0072 | 0.6709 | 0.118059 |
| 1 | 8427 | 1.2973 | 0.4795 | 0.008 | 0.254 | 0.0132 | 1.2185 | 0.194837 |
| 2 | 20809 | 2.6161 | 0.9145 | 0.0158 | 0.2579 | 0.0552 | 5.2793 | 0.683883 |
| 3 | 35407 | 3.9348 | 1.3459 | 0.0245 | 0.2623 | 0.1428 | 13.6283 | 1.47371 |
| 4 | 51666 | 5.2535 | 1.7768 | 0.0343 | 0.2671 | 0.3252 | 31.0298 | 2.579816 |
| 4.7 | 63870 | 6.1766 | 2.0785 | 0.0418 | 0.2709 | 0.666 | 63.4897 | 3.552158 |

Table B-16: ROP at 30 ft/r

| 30 ft/r | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **$U_a$ (ft/s)** | **Re** | **$U_s$ (ft/s)** | **$U_m$ (ft/s)** | **$c_s$** | **$c_m$** | **$t_m$ (in)** | **$\tau_{dis}$ ($lb/ft^2$)** | **dpz /dz (psi/ft)** |
| 0.75 | 5739 | 0.9762 | 0.3715 | 0.0061 | 0.253 | 0.0072 | 0.6829 | 0.119826 |
| 1 | 8353 | 1.3059 | 0.4823 | 0.008 | 0.254 | 0.0132 | 1.2348 | 0.19707 |
| 2 | 20717 | 2.6246 | 0.9173 | 0.0159 | 0.2579 | 0.0552 | 5.3181 | 0.68803 |
| 3 | 35302 | 3.9433 | 1.3487 | 0.0246 | 0.2623 | 0.144 | 13.7007 | 1.479847 |
| 4 | 51551 | 5.2621 | 1.7796 | 0.0343 | 0.2672 | 0.3276 | 31.1955 | 2.588057 |
| 4.7 | 63749 | 6.1852 | 2.0813 | 0.0419 | 0.271 | 0.6732 | 64.1546 | 3.561957 |

Table B-17: ROP at 15 ft/r

| 15 ft/r | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **$U_a$ (ft/s)** | **Re** | **$U_s$ (ft/s)** | **$U_m$ (ft/s)** | **$c_s$** | **$c_m$** | **$t_m$ (in)** | **$\tau_{dis}$ ($lb/ft^2$)** | **dpz /dz (psi/ft)** |
| 0.75 | 5689 | 0.9826 | 0.3737 | 0.0061 | 0.253 | 0.0072 | 0.6921 | 0.121157 |
| 1 | 8298 | 1.3123 | 0.4845 | 0.008 | 0.254 | 0.0132 | 1.2472 | 0.198753 |
| 2 | 20648 | 2.631 | 0.9194 | 0.0159 | 0.258 | 0.0564 | 5.3453 | 0.691147 |
| 3 | 35224 | 3.9498 | 1.3508 | 0.0246 | 0.2623 | 0.144 | 13.7589 | 1.484469 |
| 4 | 51465 | 5.2685 | 1.7817 | 0.0344 | 0.2672 | 0.3288 | 31.3208 | 2.594266 |
| 4.7 | 63658 | 6.1916 | 2.0834 | 0.042 | 0.271 | 0.678 | 64.6705 | 3.569329 |

**Results of the Annular Size:**

Table B-18: Annular Size of 5x2.75 in

| Annular size 5x2.75 in | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **$U_a$ (ft/s)** | **Re** | **$U_s$ (ft/s)** | **$U_m$ (ft/s)** | **$c_s$** | **$c_m$** | **$t_m$ (in)** | **$\tau_{dis}$ (lb/ft$^2$)** | **dpz /dz (psi/ft)** |
| 0.75 | 5201 | 0.9159 | 0.3572 | 0.0063 | 0.2532 | 0.006 | 0.6068 | 0.121797 |
| 1 | 7543 | 1.2287 | 0.4648 | 0.0084 | 0.2542 | 0.012 | 1.1123 | 0.200862 |
| 2 | 18605 | 2.4798 | 0.8875 | 0.0168 | 0.2584 | 0.0516 | 4.9068 | 0.704659 |
| 3 | 31644 | 3.7309 | 1.3068 | 0.0261 | 0.263 | 0.1356 | 12.9035 | 1.519337 |
| 4 | 46167 | 4.982 | 1.7257 | 0.0366 | 0.2683 | 0.3204 | 30.6067 | 2.66251 |
| 4.5 | 53896 | 5.6076 | 1.9351 | 0.0424 | 0.2712 | 0.576 | 54.9139 | 3.363273 |

Table B-19: Annular Size of 5x1.9 in

| Annular size 5x1.9 in | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **$U_a$ (ft/s)** | **Re** | **$U_s$ (ft/s)** | **$U_m$ (ft/s)** | **$c_s$** | **$c_m$** | **$t_m$ (in)** | **$\tau_{dis}$ (lb/ft$^2$)** | **dpz /dz (psi/ft)** |
| 0.75 | 5806 | 0.8967 | 0.3417 | 0.0051 | 0.2526 | 0.006 | 0.5708 | 0.096172 |
| 1 | 8427 | 1.2022 | 0.4438 | 0.0067 | 0.2533 | 0.0108 | 1.034 | 0.157857 |
| 2 | 20809 | 2.4242 | 0.8433 | 0.0133 | 0.2567 | 0.04608 | 4.4044 | 0.546827 |
| 3 | 35407 | 3.6462 | 1.2388 | 0.0204 | 0.2602 | 0.11592 | 11.0581 | 1.169028 |
| 4 | 51666 | 4.8681 | 1.6335 | 0.0281 | 0.264 | 0.24972 | 23.8208 | 2.034187 |
| 4.5 | 60319 | 5.4791 | 1.8308 | 0.0322 | 0.2661 | 0.3708 | 35.3667 | 2.561147 |
| 4.9 | 67468 | 5.9679 | 1.9887 | 0.0357 | 0.2678 | 0.55956 | 53.3725 | 3.029405 |

Table B-20: Annular Size of 8x4.5 in

| Annular size 8x4.5 in | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $U_a$ (ft/s) | Re | $U_s$ (ft/s) | $U_m$ (ft/s) | $c_s$ | $c_m$ | $t_m$ (in) | $\tau_{dis}$ (lb/ft$^2$) | dpz /dz (psi/ft) |
| 0.75 | 6351 | 0.8249 | 0.3103 | 0.004 | 0.252 | 0.0048 | 0.4737 | 0.058724 |
| 1 | 9201 | 1.1076 | 0.4027 | 0.0053 | 0.2527 | 0.0084 | 0.8537 | 0.095908 |
| 2 | 22660 | 2.2381 | 0.7626 | 0.0104 | 0.2552 | 0.0372 | 3.5294 | 0.327081 |
| 3 | 38521 | 3.3687 | 1.1175 | 0.0157 | 0.2579 | 0.0888 | 8.4471 | 0.692165 |
| 4 | 56183 | 4.4992 | 1.4712 | 0.0214 | 0.2607 | 0.1752 | 16.7413 | 1.195274 |
| 4.5 | 65583 | 5.0645 | 1.6479 | 0.0244 | 0.2622 | 0.24 | 22.8782 | 1.499932 |
| 4.9 | 73349 | 5.5167 | 1.7892 | 0.0268 | 0.2634 | 0.3084 | 29.4046 | 1.76969 |
| 5.8 | 91554 | 6.5342 | 2.1073 | 0.0327 | 0.2664 | 0.6516 | 62.188 | 2.463557 |

Table B-21: Annular Size of 8.75x4.5 in

| Annular size 8.75x4.5 in | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $U_a$ (ft/s) | Re | $U_s$ (ft/s) | $U_m$ (ft/s) | $c_s$ | $c_m$ | $t_m$ (in) | $\tau_{dis}$ (lb/ft$^2$) | dpz /dz (psi/ft) |
| 0.75 | 7229 | 0.8071 | 0.2966 | 0.0031 | 0.2516 | 0.0048 | 0.4441 | 0.04368 |
| 1 | 10480 | 1.0831 | 0.3843 | 0.004 | 0.252 | 0.0084 | 0.7924 | 0.071047 |
| 2 | 25832 | 2.1871 | 0.7245 | 0.0078 | 0.2539 | 0.0336 | 3.1919 | 0.239485 |
| 3 | 43928 | 3.2911 | 1.0589 | 0.0118 | 0.2559 | 0.078 | 7.4547 | 0.502787 |
| 4 | 64081 | 4.3951 | 1.3918 | 0.0159 | 0.2579 | 0.15 | 14.2506 | 0.863008 |
| 4.5 | 74809 | 4.9471 | 1.558 | 0.018 | 0.259 | 0.1992 | 19.0066 | 1.080107 |
| 4.9 | 83667 | 5.3887 | 1.6909 | 0.0197 | 0.2599 | 0.2484 | 23.7181 | 1.271852 |
| 5.8 | 104440 | 6.3823 | 1.99 | 0.0238 | 0.2619 | 0.4152 | 39.6271 | 1.76306 |
| 6.3 | 116440 | 6.9343 | 2.1561 | 0.0261 | 0.2631 | 0.6072 | 57.9539 | 2.072017 |

# Appendix C

## Correlation of Moving-bed Built up under Different Drilling Parameters

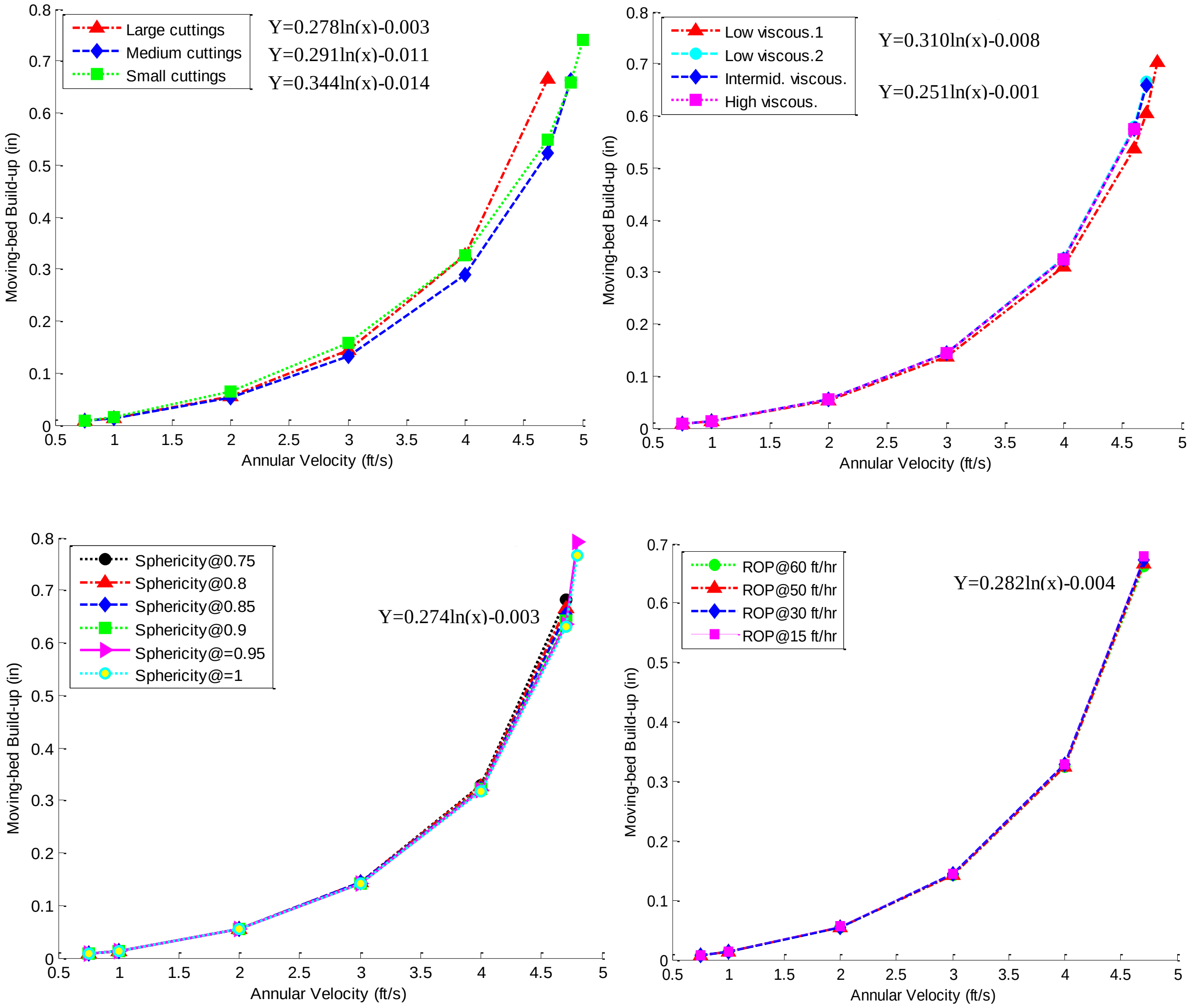


Figure C-1a: Moving-bed built up

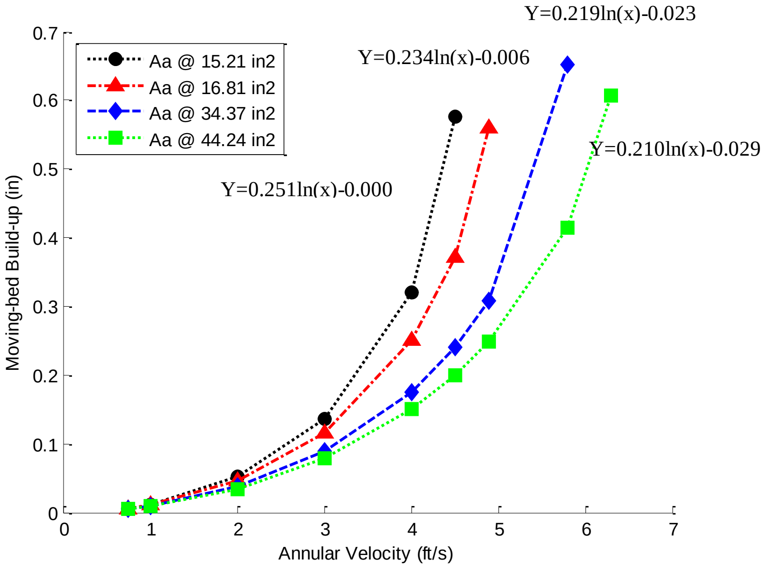


Figure C-1b: Moving-bed built up

# Appendix D

## Dimensionless Analysis

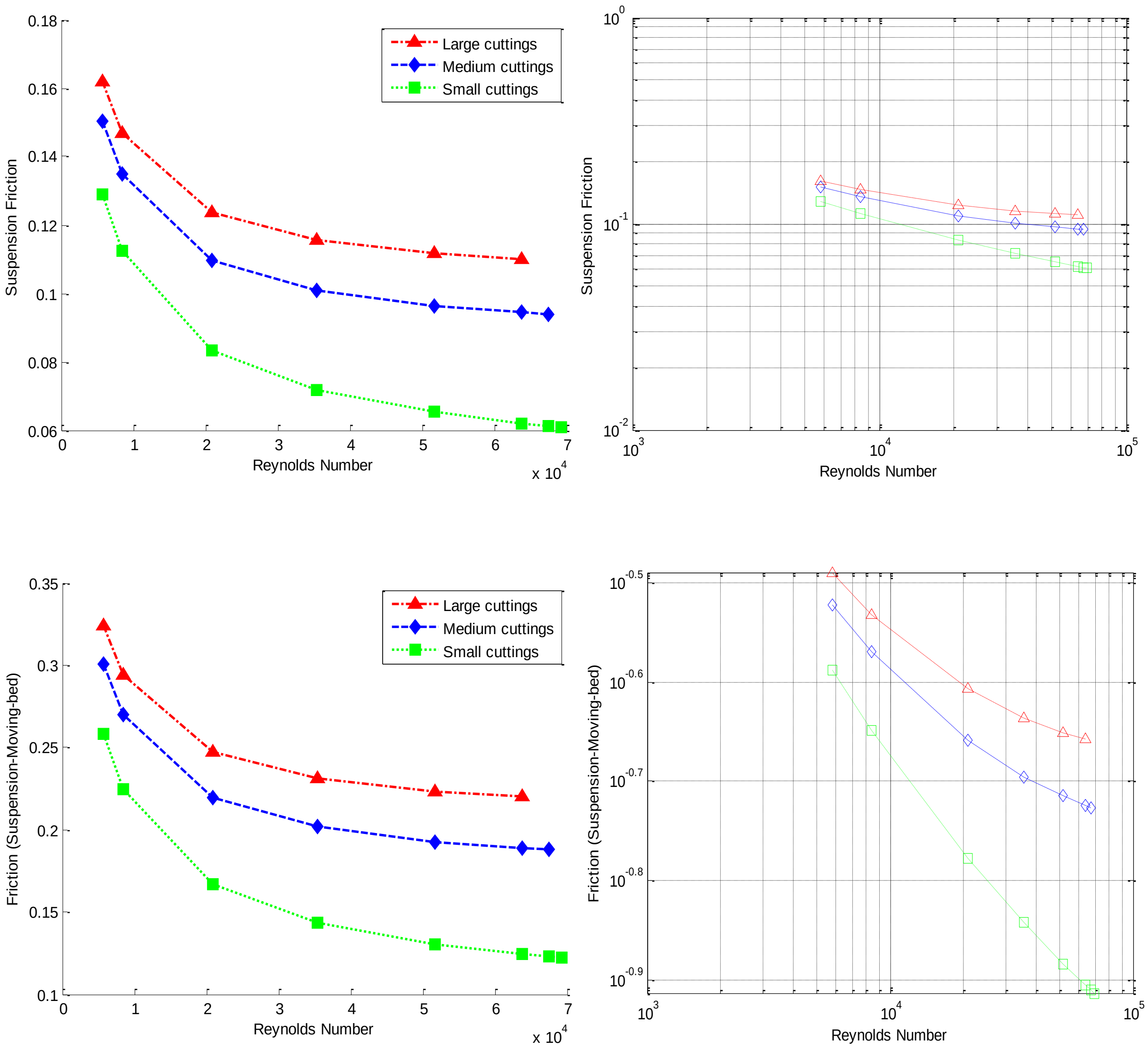


Figure D-1a: Frictions at different cuttings sizes

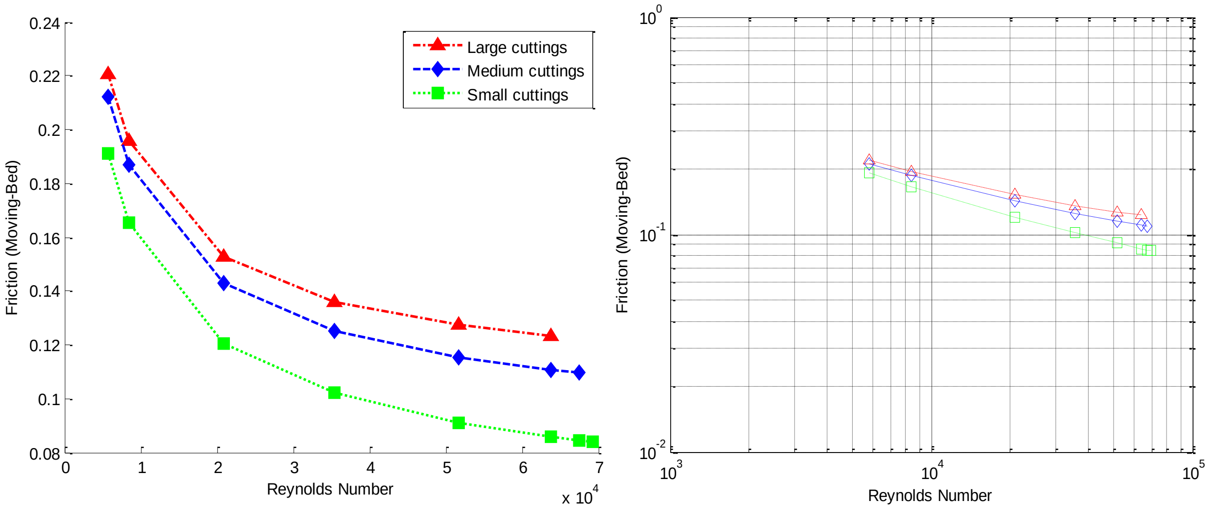


Figure D-1b: Frictions at different cuttings sizes

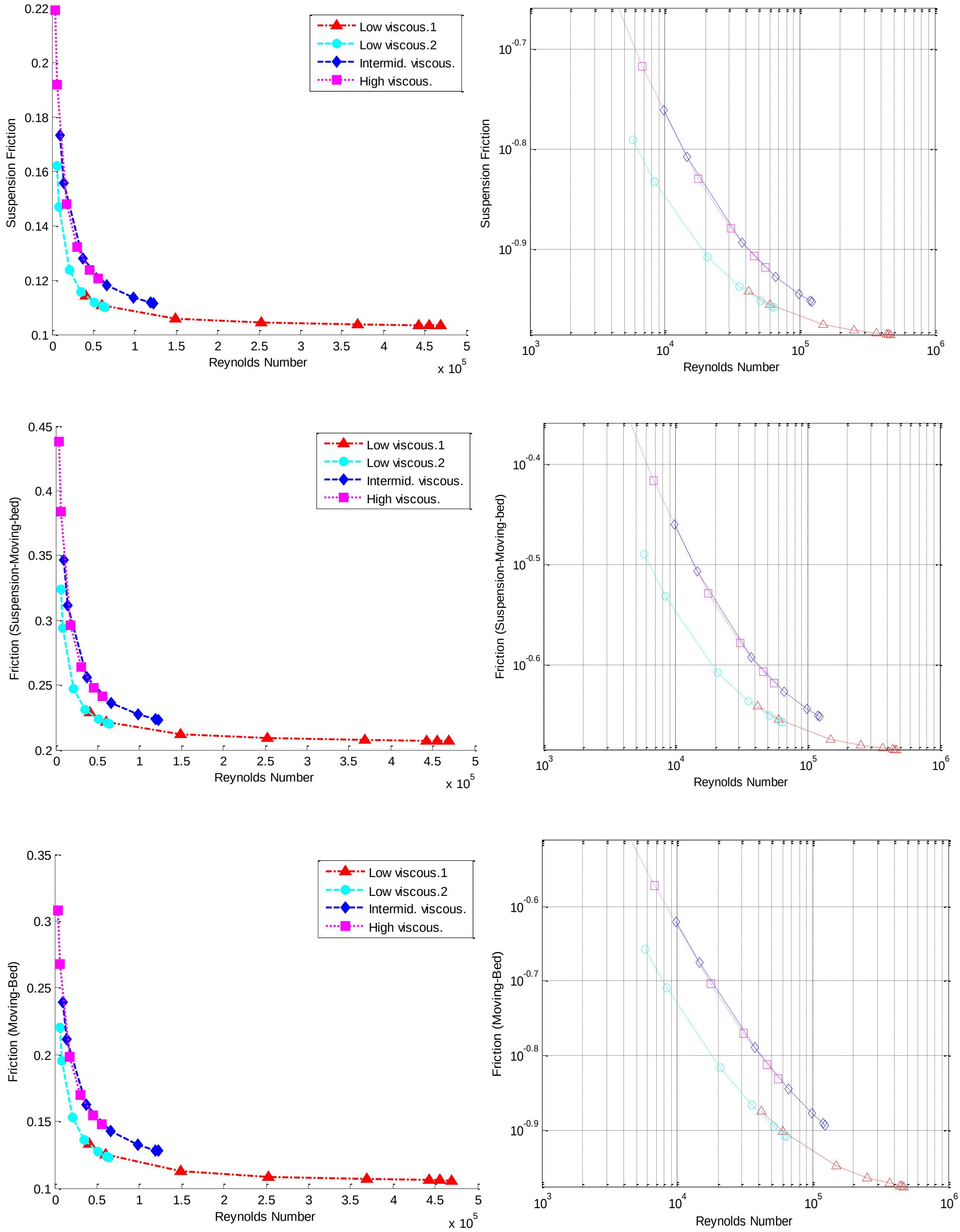


Figure D-2: Frictions at different mud viscosity

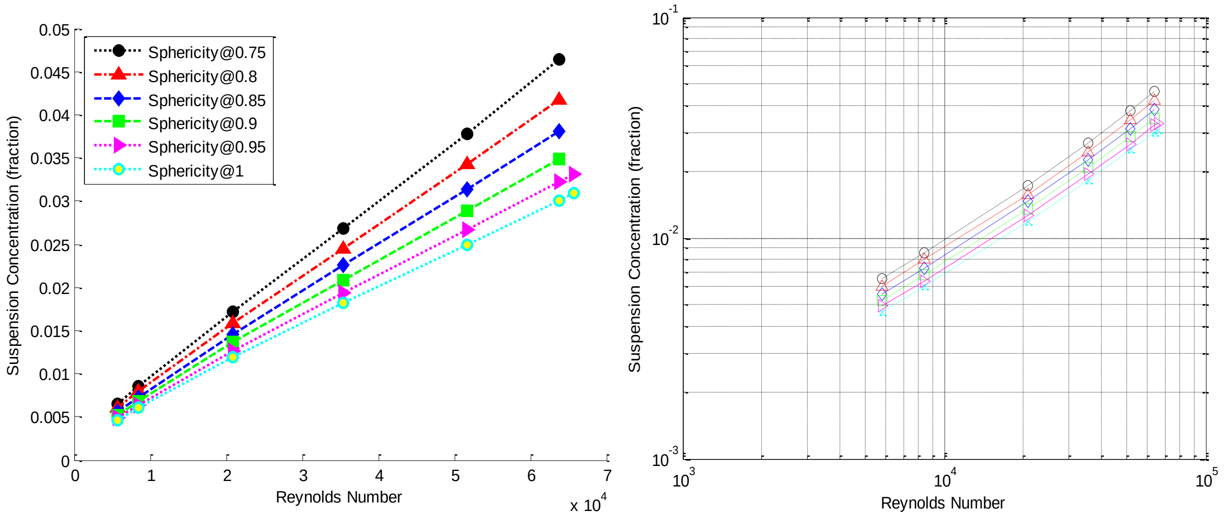


Figure D-3: Suspension concentration at different cuttings sphericity

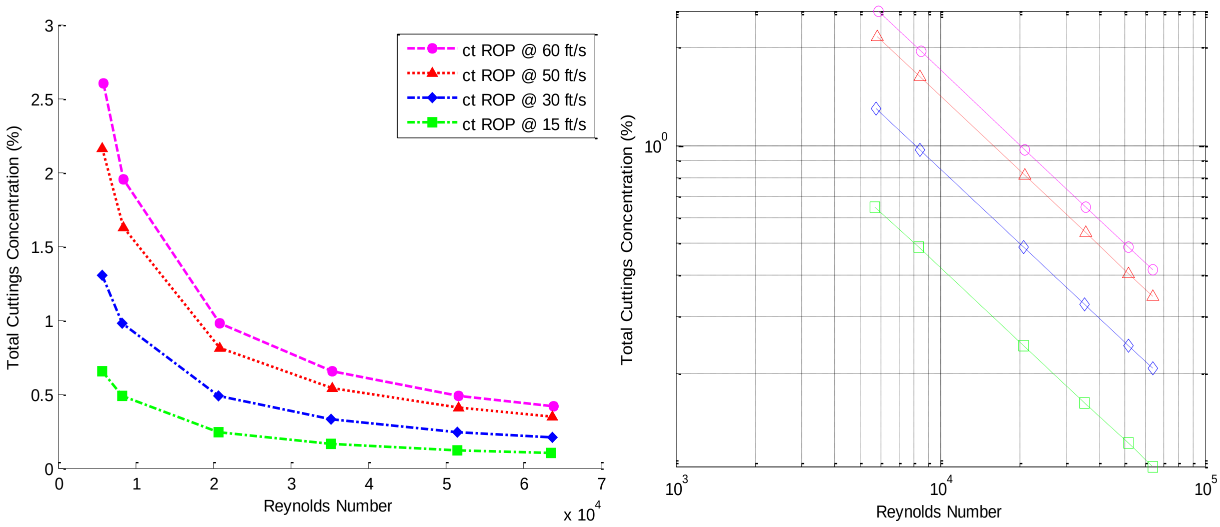


Figure D-4: Total cuttings concentartion at different ROP

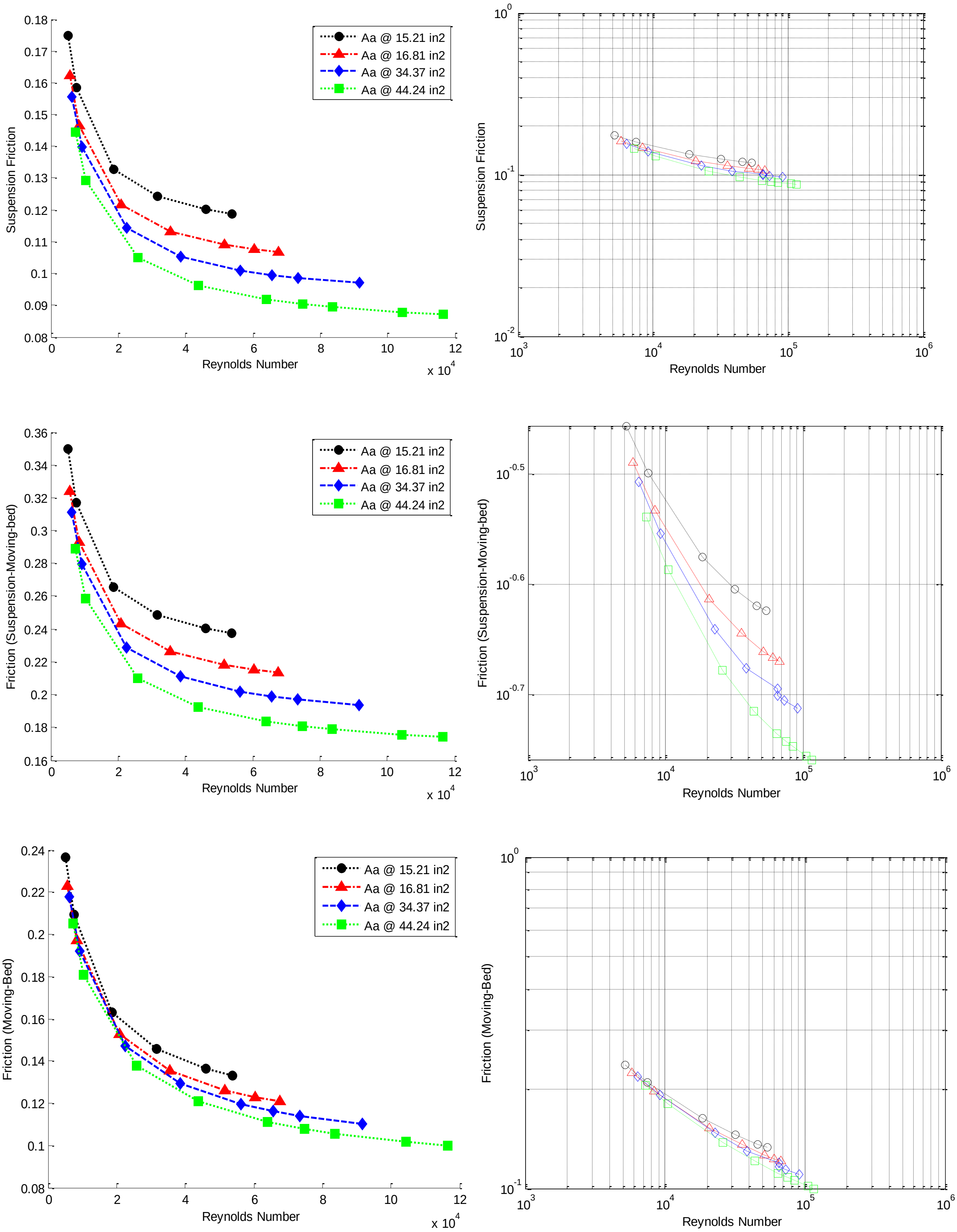


Figure D-5: Frictions with different annular sizes.