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ABSTRACT

Efficient cuttings transport and hole cleaning is very important for obtaining an effective drilling operation. In inclined and horizontal drilling, hole cleaning issues is a common and complex problem. This thesis explores the impact of various drilling parameters, and how they affect the required flow velocity and flow rate required for effective cuttings transport.

The main objectives of the thesis are outlined as follows:

- To make a sufficient review of previous studies;
- Explain the fundamentals of the cuttings transport parameters and definitions;
- To introduce and explain in great details the empirical model focusing on the models of Larsen and Rubiandini;
- To make an introduction to the mechanistic modeling approach focusing on demonstrating the complexity of these models;
- To apply Larsen's and Rubiandini's models in order to compare and identify similarities and differences between the models;
- To present some field experience from offshore;
- To draw conclusions about what we can learn from earlier studies and research.

The thesis employs two models developed by an empirical approach, namely Larsen's model and Rubiandini's model. Two simulation scenarios have been considered. First, we have compared the models using the cases defined by Larsen from his experimental work. Then, an example well has been considered which mimics more operational conditions. Moreover, the thesis presents the mechanistic two-layer model developed by Kamp and Rivero, and demonstrates how the model has to be reformulated mathematically before a numerical method can be used for solving the model.

The analysis of the two empirical models showed that both models show the same trend for required cuttings transport flow velocity and flow rate when drilling parameters, such as mud weight, ROP, mud rheology and drill-pipe diameter varied. For the horizontal case, we observe that Larsen predicts flow rate that are not far from the flow rates typical seen in operations, however it slightly over predicts required cuttings transport velocity. Rubiandini's model seems to predict high flow rate required for cuttings transport. However, for the vertical case, the predicted rate seems to coincide with flow rates typical in operations. The main advantage of Rubiandini's model is that in his work, he considered RPM as a variable that could affect the cuttings transport.

The results also indicate that Larsen's model and Rubiandini's model show the opposite effect on required cuttings transport velocity when the cuttings size is a variable parameter. In the Larsen's model, smaller cuttings required higher flow velocity to be transported, while in

the Rubiandini's model, the opposite is observed, namely larger cuttings need a higher flow velocity for transport in the wellbore.

In the conclusion, several recommendations on how to achieve better cuttings transport and hole cleaning are listed.

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1. INTRODUCTION

Transportation of cuttings is a mechanism that is a vital factor for a good drilling program. In directional and horizontal drilling, hole cleaning is a common and costly problem. Ineffective removal of cuttings can result in several problems, such as bit wear, slow drilling rate, increased ECD (which can lead to formation fracturing), high torque, drag, and in the worst case, the drill pipe can be stuck. If this type of situation is not handled properly, the problem can escalate to side tracking or loss of well, at worst.

Cuttings transport is controlled by many variables such as well inclination angle, hole and drill-pipe diameter, rotation speed of drill pipe (RPM), drill-pipe eccentricity, rate of penetration (ROP), cuttings characteristics like cuttings size and porosity of bed and drilling fluids characteristics like flow rate, fluid velocity, flow regime, mud type and non - Newtonian mud rheology. The key factors for optimizing hole cleaning is a result of good well planning, good drilling fluid properties, and good drilling experience.

Cuttings transport, especially in highly inclined wellbores, is a complex problem. Therefore, a large number of papers have been published to explore and solve this problem over the last 30 years. An extensive experimental work has been carried out by several universities[5, 17, 21, 28, 29, 32, 35, 37], including the University of Tulsa[3, 7-10, 13, 31, 34, 36], Heriot-Watt University[2, 12, 26], and different petroleum companies and organizations [1, 3, 4, 9, 11, 14-16, 18- 20, 22-26, 30, 33, 34, 37]. The studies were directed towards investigating various parameters that affect the cuttings transportation in both vertical and horizontal wellbore and to establish correlation models for prediction purposes that could be used in drilling operations.

Today, it is common to recognize two main approaches: empirical or mechanistic (theoretical). Peden et al.[1](1990) and Larsen et al.[2](1993) have made a large number of experiments and thus, were able to develop empirical models, whereas Gavignet and Sobey[3] (1989), Kamp and Rivero[4] (1999) have developed a two-layer model by using a mechanistic approach. Later Rubiandini[5] (1999), based on Moore's[6] vertical slip-velocity model, Larsen's empirical model and Peden's experiments developed his own model to calculate minimum fluid flow velocity both in vertical and horizontal wellbores. These publications were mainly qualitative studies and experimental studies, and several models and corrections have been proposed. However, cuttings transport remains being one of the major problems during drilling operations.

In addition, there are different models that are applied for vertical [6, 8, 21, 35] and inclined and horizontal[2- 4, 9-17, 19, 24, 26-28, 31, 33, 34, 36, 37] wellbores. In this research, the focus was primary on the models for the inclined and horizontal wellbores. However, the model for the vertical wellbore is also presented in this study in order to demonstrate the complexity of the models, and the cuttings transport problem in general.

The purpose of this study is to establish an overview of the previously published studies that started from early 1980's until today. The summary of the literature review is presented in chapter 2. The majority of investigations on the vertical wellbore hole cleaning were performed mainly during the 1970's. As new technologies in directional drilling were developed, the research was focused primarily on cuttings transport in inclined and horizontal wellbores. Therefore, this thesis is mainly aimed on inclined and horizontal wellbore cuttings transport. Since this topic has become highly exposed for development and new studies for the last decades, it is possible that the literature review is not fully covered in this research.

The main objectives of this thesis are:

- To make a sufficient review of the previous studies;
- Explain the fundamentals of the cuttings transport parameters and definitions;
- To introduce and explain in great details the empirical model focusing on the models of Larsen and Rubiandini;
- To make an introduction to the mechanistic modeling approach (e.g. Kamp's model) to demonstrate the complexity of this approach;
- To apply Larsen's and Rubiandini's models in order to compare and identify differences between these models by using MatLab software;
- To present some field experience from offshore;
- To draw conclusions about what we can learn from earlier studies and research.

The simulations were based on the rheological data, drilling parameters, and cuttings properties used by Larsen during his study and experiments and practical drilling data from an 8 ½" well section. The figures, graphs, and charts used in this thesis were made using MatLab software.

The thesis contains 10 chapters, a reference list, and 6 attachments. Chapter 1 presents the introduction to the cuttings transport challenge and defines the objectives of the thesis. Chapter 2 gives the literature background and summary of the review that have been covered in this research. In chapter 3, the basic theory [7, 38] and equations are presented, explaining the definitions and parameters that have been used both in the current research and literature review. Larsen's empirical model[2] and his correlations are explained in details in chapter 4, while chapter 5 covers the Peden's model[1] and forces that affect the transport of cuttings in the wellbore. In chapter 6, the Rubiandini's model[5] is described and the structure of the model for calculation of the minimum fluid flow velocity is explained. Chapter 7 presents the basics of the Kamp's mechanistic model[4], the introduction of the Gavignet's[3] two-layer model, and how we possibly can transform the equations mathematically in order to achieve a matrix form that can be solved numerically. Chapter 8 contains simulations of the two models, namely Larsen's and Rubiandini's models, and these are later compared with each other. The differences between these two models by varying different parameters are discussed in the chapter 9, along with practical field observations. Chapter 10 finalizes this research and some conclusions on the study are drawn.

2. BACKGROUND AND LITERATURE REVIEW

This literature review covers cuttings transport studies and analysis for both vertical and horizontal wellbores for the last 30 years. Most of cuttings transport studies in the inclined and horizontal wellbores started in the 1980's[3, 7-11]. Yet, the existing models and equations for solving the challenges of cuttings transport and hole cleaning appeared to be ineffective. Therefore, the new models and techniques were developed in recent years[35-37].

In 1981, *Iyoho* and *Azar*[7] presented a new model for creating analytical solutions to the problems of non-Newtonian fluid flow through eccentric annuli. During the study, they achieved some important results. First, it was observed that flow velocity was reduced in the eccentric annulus. It was a crucial observation for the directional drilling since drill pipe tended to lie against the hole. Secondly, the study had a practical application that included the calculation of velocity distribution in chemical processes that were involving fluid flow through eccentric annuli.

In 1983, *Hussaini* and *Azar*[8] conducted an experimental study on behavior of cuttings in a vertical annulus. They focused on studying the effect of various factors such as annular velocity, apparent viscosity, yield point to plastic viscosity ratio, and particle size effect on the carrying capacity of drilling fluids (see chapter 3 for definitions). The last objective of their study was verifying the Ziedler's transport model by using actual drilling fluids. They concluded that annular fluid velocity had a major effect on the carrying capacity of the drilling fluids, while other parameters had an effect only at low to medium fluid annular velocities. Hussaini and Azar were also able to conclude that Ziedler's particle annular concentration equation was valid for drilling fluids.

Tomren et al.[9] (1986) performed an experimental study of cuttings transport in directional wells. In this research, they used a 40 ft (12, 2 m) pipe. Several types of drilling fluids and different flow regimes were tested. The annulus angles varied from 0° to 90° degrees and actual drilling cuttings were used in this experiment. Tomren et al. performed 242 different tests in total, varying angles of pipe inclination, pipe eccentricities, and different fluid flow regimes (laminar and turbulent). Several conclusions on cuttings transport in inclined, eccentric annulus were drawn. First, the effective flow area was reduced by a growing formation cuttings bed at high liquids rates for angles that were greater than 40° degrees. The studies indicated that the major factors, such as fluid velocity, hole inclination, and mud rheology, had to be considered during directional drilling. This research proved that fluids with higher viscosity would give better cuttings transport, within a laminar flow regime. It was documented that pipe rotation produced rather slight effect on transport performance in an inclined wellbore. The experiments showed that hole eccentricity affected bed thickness and particle concentration in the pipe. Thus, for angles of inclination less than 35°, the negative-eccentricity case gave the worst cuttings transport for all flow rates. For angles of inclination greater than 55°, the positive-eccentricity case gave the worst transport as well. Tomren et al. could concluded that angles between 35° and 55° degrees were critical angles since they caused bed forming and a bed sliding downwards against the flow.

In 1986, *Okrajni* and *Azar*[10] performed an experiment on effect of mud rheology on annular hole cleaning in deviated wells. They focused on mud yield point [YP], plastic viscosity [PV] and YP/PV ratio. Three separate regions for cuttings transport, namely 0° to 45°, 45° to 55° and 55° to 90° degrees were identified. The observations showed that laminar flow was more effective in low angle wellbore (0° to 45° degrees) for hole cleaning. In the wellbore with the inclination of 55° to 90° degrees, the turbulent flow had high effect on cuttings transport, while in the intermediate inclination (from 45° to 55° degrees), turbulent and laminar flow had the same effect on the cuttings transport. The highest annular cuttings concentration had been observed at critical angle of inclination, between 40° and 45° degrees, when flow rate was relatively low. In laminar flow, drilling fluid with high yield point (YP) and high plastic viscosity ratio (PV) provided a better hole cleaning. Effect of drilling fluid yield values was considerable in low inclined wellbore (0° to 45°), and it gradually became minor and insignificant in the high inclination wellbore (55° to 90°). Okraini and Azar recommended laminar flow for hole cleaning in interval 0° and 45° degrees, and a turbulent flow for hole cleaning in interval 55° and 90° degrees. The effect of drilling fluid yield values was more notable for low annular fluid velocities (laminar flow). In turbulent flow, cuttings transport was not affected by the mud rheological properties but only by the momentum force.

In 1989, *Gavignet* and *Sobey*[3] presented a cuttings transport mechanistic model. In this study, they developed a two-layer model for cuttings transport in an eccentric annulus with a Non-Newtonian drilling fluid. The scientists established the critical flow rate above which a bed would not form. According to their calculations, this critical flow rate would occur when the flow was in a turbulent phase. The study indicated that this criterion was strongly dependent on drill-pipe eccentricity, cuttings size, drill-pipe outside diameter and hole diameter. On the contrary, the defined critical flow was only slightly dependent on rheology, ROP, and inclination angle that was greater than 60°. Gavignet and Sobey indicated that friction coefficient of the cuttings against the wall affected highly the bed formation at high angles of deviation. Gavignet and Sobey compared their mechanistic model with the experimental results of *Tomren et al.* [8] studies.

In 1989, *Brown et al.*[11] performed analysis on hole cleaning in deviated wells. The study indicated that the most effective drilling fluid for hole cleaning was water in turbulent flow. However, in low angle wells, with the viscous HEC fluid, cuttings could be transported with lower annular velocity. From the experimental observations, it was concluded that hole angles between 50° and 60° degrees presented the most difficult sections for hole cleaning in an inclined wellbore.

In 1990, *Ford el al.*[12] performed an experimental study of drilled cuttings transport in inclined wellbore. During this research, two different cuttings transport mechanisms were presented; the first where the cuttings were transported to surface by a rolling/sliding motion along the lowest side of the annulus and the second, where the cuttings were moved in suspension in the circulating fluid. The main difference between these two mechanisms was that the second mechanism required a higher fluid velocity than the first one. They identified MTV (Minimum transport velocity), which was the minimum velocity needed to make sure that the cuttings were moving upward in the borehole annulus. MTV was dependent on many different parameters, such as rheology of drilling fluid, hole angle, drill-pipe eccentricity, fluid velocity in annulus, cuttings size etc. The scientists observed that increasing viscosity of circulating fluid would lead to decreasing of MTV for cuttings both rolling and in suspension form. The experiments indicated that in turbulent flow, water was a very effective transport fluid.

In 1990, *Peden et al.*[1] presented an experimental method, which investigated the influence of different variables in cuttings transport, such as hole angle, fluid rheology, cuttings size, drill pipe eccentricity, circulation ratio, annular size, and drill-pipe rotation on cuttings transport efficiency using a concept of Minimum Transport Velocity (MTV). The concept presumed that at lower minimum transport velocity, a wellbore would be cleaned more effectively. Peden et al. concluded that hole angle had a strong effect on hole cleaning. They also defined that hole angles between 40° and 60° degrees were the worst angles for transportation of cuttings for both rolling and in suspension form. The observations showed that smaller concentric annuli required a lower MTV for hole cleaning than larger ones, and effective hole cleaning was strongly dependent on the intensity of turbulent flow in annulus. In addition, the pipe rotation seemed to have no influence on hole cleaning. At all wellbore inclinations, smaller cuttings were transported most effectively when the fluid viscosity was low. In the interval angle between 0° and 50° degrees, large cuttings were transported more effectively with high viscosity drilling fluid.

In 1991, *Becker et al.*[13] presented a method for mud rheology correlations. They proved that mud rheological parameters improved cuttings transport performance with the low–shear rate viscosity, especially the 6-rpm Fann V-G viscometer dial reading. They indicated that in a wellbore angle from vertical to 45° degrees, cuttings transport performance was more effective when drilling fluid was in a laminar flow regime. Furthermore, when wellbore inclinations was higher than 60° degrees from vertical, cuttings transport performance was more effective when drillings fluid was in a turbulent flow regime. Influence of mud rheology on the cuttings transport was considerably greater at a laminar flow regime in the vertical wellbore, but mud rheology had no significant effect on the cuttings transport when the flow regime was turbulent.

Luo et al.[14] (1992) performed a study on flow-rate predictions for cleaning deviated wells. They developed a prediction model for critical flow rate or the minimum flow rate required to remove cuttings from low side of the wellbore or to prevent cuttings accumulation on the low side of the annulus in deviated wells. The model was proven by experimental data obtained from an 8 inch wellbore. During their study, a model and a computer program were developed to predict the minimum flow rate for hole cleaning in deviated wellbore. The model was later simplified into a series of charts to facilitate rig-site applications.

Martins and *Santana*[15] (1992) presented a two-layer mechanistic model in order to describe the stratified flow of solid non-Newtonian fluid mixture in horizontal and near horizontal eccentric annuli. The model consisted of the top layer that was a heterogeneous suspension and the bottom one, a compacted bed of solids. The model was applied to several flow regimes that characterized the solid-liquid horizontal flows. A computer simulator was generated from this model as a tool of designing field operations. The model indicated that the use of large drill-pipe diameter, increase of fluid density, and flow rate provided possible control during drilling operations and were effective solutions of drilling issues.

In 1992, *Sifferman* and *Becker*[16] presented a paper, where they evaluated hole cleaning in full-scale inclined wellbores. This hole cleaning research identified how different drilling parameters, such as annular fluid velocity, mud density, mud rheology, mud type, cuttings size, ROP, drill pipe rotation speed (RPM), eccentricity of drill pipe, drill pipe diameter and hole angle affected cuttings accumulation and bed buildup. The results of the experiment indicated that mud annular velocity and mud density were the most important variables that had influence on cuttings-bed size. Thus, it was observed that cuttings beds decreased considerably by a small increase in mud weight. Drill-pipe rotation and inclination angle had also significant effect on cuttings-bed build-up. The experiment showed that beds forming at inclination angles between 45° and 60° degrees might slide or tumble down, while at the angle between 60° and 90° degrees from vertical, cuttings bed was less movable. They also concluded that cuttings bed was accumulated easier in oil-based mud than in water-based mud.

In 1993, *Larsen et al.*[2] developed a new cuttings transport model for high inclination angle wellbores. The model was based on an extensive experimental test on annular hole cleaning in a wellbore with angle interval from 55° to 90° degrees from vertical. The experiment was focused on the annular fluid velocity required to prevent cuttings from accumulating in the wellbore. The aim of the developed model was to predict the minimum fluid velocity that was necessary to keep all cuttings moving.

During the research, the three definitions were used:

- Critical transport fluid velocity (CTFV), which was the minimum flow velocity that needed to keep continuously upward transport of cuttings to surface.
- Cuttings transport velocity (CTV) defined as the velocity of cuttings particles during transport.
- Sub-Critical fluid flow (SCFF) meaning that for any flow velocity that was below critical transport fluid velocity (CTFV), cuttings would start to accumulate in the wellbore.

The experimental study was conducted in order to evaluate the effect of the factors, such as flow rate, angle of inclination, mud rheology, mud density, cuttings size, drill pipe eccentricity, ROP, and drill pipe rotation (RPM) on the CTFV and SCFF. Based on wide experimental studies, a set of simple empirical correlations was developed to predict critical transport fluid velocity (CTFV), sub-critical fluid flow (SCFF), and cuttings transport velocity (CTV).

In 1993, *Doron* and *Barnea*[17] presented a three-layer model for prediction of solid-liquid mixture in a horizontal pipe. This model was based on laboratory observations as well as analysis of the flow, with some basic assumptions, and was a development of the previously published two-layer model. The improved three-layer model was described by a cuttings bed consisting of two beds, a stationary bed at the bottom, a moving bed layer above it, and a heterogeneous mixture at the top. The model results were compared to previously published experimental data and the agreement was quite satisfactory. The model also showed significant improvements compared to the two-layer model. Thus, the three-layer model predicted the existence of a stationary bed for all sets of operational conditions, such as solids density and pipe diameter. However, it was indicated that this model performance could be improved by introducing the some additional variables.

In 1993, *Lockett et al.*[18] presented results from a three-year long investigation of Taylor vortices influence on drilling operation. In their study, they used a computer simulation to monitor both fluid flow and particle transport. At the end of the study, some conclusions were drawn. First, this study was able to demonstrate that if Taylor vortices would be present in the drilling annulus, cuttings forming a bed on the low side of a horizontal annulus would experience an oscillatory force due to the passage of vortices overhead. Secondly, it was also shown that particles in both vertical and horizontal annulus might be suspended near one of the eyes of the vortices for a long time. At last, this study concluded that although numerical simulations allowed a wide range of situations to be studied, validation against the experimental data was important.

In 1994, *Luo et al.*[19] presented a simple graphical technique to determine hole cleaning requirements for a range of hole sizes. Further, the method was presented by a set of charts that were adjusted to various hole size and were valid for the typical North Sea drilling conditions. The set of charts included the controllable drilling variables like, fluid flow rate, rate of penetration (ROP), mud rheology, mud weight, and flow regimes. To simplify the study, it was decided to ignore the unverifiable variables, such as drilling eccentricity, cuttings density, and cuttings size. One of the main key variables in these charts was mud rheology, and it was indicated that effect of mud rheology depended on the flow regimes.

In 1994, *Rasi*[20] performed a study on hole cleaning in large (larger than 10-inches in diameter) high-angle (50° degrees from vertical or higher) wellbore. The result of this work was development of a hole cleaning design tool. The tool was based on fluid mechanics principles, experimental data, and field data. By using the tools, it was allowed to assess pump flow rate requirements, to optimize fluid rheology and drill string design. Although, the tool was already in use in the design of wells that experience the hole cleaning problems, additional research was still needed to address the remaining questions. According to Rasi[20], the impact of drilling operations required serious further studies.

Same year, *Belavadi* and *Chukwu*[21] had an experimental study on the cuttings transport where they studied the parameters affecting cutting transportation in a vertical wellbore. For better understanding of parameters that affect cuttings transport in a vertical well, a simulation unit was constructed and cuttings transport in the annulus was observed. The data collected from this simulation was graphically correlated in a dimensionless form versus transport ratio. The result from this analysis showed that density difference ratio between cuttings and drilling fluid had a major effect on the cuttings transport. Belavadi and Chukwu concluded that increase in the fluid flow rate would increase cuttings transport performance in the annulus, when the drilling fluid density is high. In contrary, at low drilling fluid density, this effect is neglected when cuttings have large diameter. They concluded that transport of small sized cuttings would increase, when drill-pipe rotation and drilling fluid density was high.

In 1994, *Clark* and *Bickham*[22] developed a new mechanistic model that would allow completing a cuttings transport analysis for the entire well, from surface to the bit. This cuttings transport model was developed for the various modes of particle transport: settling, lifting, and rolling, where each transport mode was dominant within a certain range of wellbore angles. The model predictions were later compared with experimental data and showed a good agreement. The computer version of the model was used for examination of situations where poor cuttings transport caused drilling problems. Therefore, according to Clark and Bickham[22], this model was helpful for identifying potential solutions, and for designing well paths for optimal hole cleaning.

In 1995, *Guild et al.*[23] presented a hole cleaning program. The objective of this program was to improve the extended reach drilling performance by avoiding stuck pipe and tight holes, and by maximizing daily drilling performance. It was concluded that by monitoring torque and drag, the drilling performance would improve. This hole-cleaning program also contributed to drilling performance by improving the general understanding of hole cleaning as the well being drilled.

Martins et al.[24] (1996) presented results of an extensive experimental program that was focused on the understanding the phenomena evolved in the erosion of a cuttings bed deposited on the lower side of a horizontal annular section. A set of correlations, based on the experimental results, was developed for prediction of bed height and critical flow rate during the circulation of a horizontal well. The results of the experiments indicated that fluid yield point (YP) was significant only in the bed erosion of eccentric annuli. However, the additional research was required to establish more accurate interpretation of fluid rheological effects. The correlations seemed to be helpful tools for optimizing of horizontal drilling and cementing operations.

In 1996, *Kenny et al.*[25] proposed a new model that combined some developments in the particle settling and rheology area. The model provided a useful tool for the planning of the hole cleaning for highly deviated wells. From the study, some important conclusions were drawn. First, some key factors (pump rate, fluid rheology, drill pipe eccentricity, and particle settling) had to be taken into account when evaluating hole cleaning in the deviated wells. Second, fluid flow index “n” was playing a major role in hole cleaning efficiency. The study also revealed that use of a single rheological parameter might lead to failure in hole cleaning analysis. Therefore, all available rheological parameters ought to be used in order to achieve sufficient hole cleaning evaluation.

Same year, *Ford et al.*[26] introduced a computer package that could be used in calculations of the minimum transport velocity (MTV) required to ensure effective hole cleaning in deviated wells. This computer program was developed based on extensive experimental[1, 12] and theoretical research program. The program was structured so that it could be used as a design and/ or analysis tool for the optimization of the cuttings transport processes. It also could be used to perform the sensitivity analysis of the cuttings transport process to changes in drilling parameters and fluid properties.

In 1996, *Martins et al.*[27] had an experimental study on dependency of the interfacial friction factor on the Reynolds number, on the ratio between particle diameter and hydraulic diameter, and on the behavior index in horizontal bed of cuttings. The experiments consisted on the visualization of the sandstone bed erosion by different polymeric solutions flowing through an annular section. A set of correlations was developed for prediction of interfacial friction factor and maximum static forces of a solid non-Newtonian fluid system. These correlations were very helpful for the development of physically based models for the evaluation of cuttings transport. Further work was advised in order to incorporate the effects of drill pipe rotation in the interfacial friction factor and in maximum static forces.

In 1996, *Nguyen* and *Rahman*[28] introduced a three-layer cuttings transport model that was based on improved understanding of the mechanism and theory of particles transport. The presented model consisted of three components - a bed of particles of uniform concentration, a dispersed layer, in which particle concentration varied, and a fluid-flow layer that could be a clear fluid or a turbulent suspension. This mathematical model allowed prediction of various modes of cuttings transport in deviated to horizontal wells. The model showed a good agreement with the experimental observations, and a computer program was developed based on this model.

In 1996, *Doron et al.*[29] presented an extension of the three-layer model published by *Doron* and *Barnea*[17]. The modified model was applicable for solid-liquid flow in inclined wellbores. New experimental data were used to validate the model result. It was stated that the model showed a good agreement with the data, regarding the pressure drop. Yet, based on observations and basic assumptions, it was advised to use the proposed model for relatively small angles of inclination. Moreover, the limit deposit velocity was over predicted, indicating that the model provided the upper limit for the limit deposit condition.

In 1996, *Hemphill* and *Larsen* [30] performed an experimental research where efficiency of water and oil-based drilling fluids in cleaning the inclined wellbore at varying fluid velocities were studied. During the research, the following definitions were established:

- Critical flow rate defined as a flow velocity at which cuttings bed starts to build-up
- Subcritical flow rate defined as a fluid velocity that is lower than the critical flow rate. In this case, cuttings accumulate in annulus.

Several major conclusions on the performance of drillings fluids were made at the end of this study. First, the fluid velocity was a key to the hole cleaning of the inclined annulus. Second, the role of mud weight was less significant than the role of fluid velocity. From the observations, it was stated that oil-based mud did not clean the wellbore as good as water-based mud when they were compared under conditions of critical flow rates and subcritical flow. Other parameters, such as mud density and flow index “n” factors, could affect cuttings transport in certain hole angle ranges.

In 1997, *Azar* and *Sanchez*[31] discussed factors that had influence on hole cleaning and their field limitations. The discussion was focused on the following factors: annular drilling fluid velocity, hole inclination angle, drill string rotation, annular eccentricity, ROP, and characteristics of drilled cuttings. Some major conclusions were drawn. The limitation on all these factors affecting the hole cleaning did existed, and therefore careful planning and simultaneous considerations on those variable were necessary. It was proven again that hole cleaning in deviated wells was a complex problem and thus, many issues in the research and in methodology were ought to be addressed before a universal solution to hole cleaning problems could be presented.

In 1998, *Philip et al.*[32] made a deterministic attempt in order to establish if vortices would play a role in the cutting transport, and if so, what fluid and system properties should be preserved so that vortices would appear in the system. In order to verify this, several experiments with a wide range of Newtonian and power law fluids in a transparent annular geometry were performed. During the study, it was observed that Taylor vortices contributed to the lift of the cuttings and aided to a better cuttings transport. In Newtonian drilling fluids, fluid viscosity increased and thus, improved the lifting capacity. In a power law drilling fluids, drilling fluids with high “n” values were more effective for cuttings transport. This study showed that drilling fluids with higher “k” values resulted in better cuttings suspension and improved cuttings transport. The experiment proved that Newtonian fluids had a better ability for cuttings transport than power law shear thinning fluids with a similar apparent viscosity. From theoretical and experimental results, it was indicated that Taylor vortices could form in all type of drillings fluids, even at the lowest rate of rotation (40 rpm).

In 1999, *Sanchez et al.*[33] performed an experimental study on the effect of drill-pipe rotation on hole cleaning during directional well drilling. In order to perform the experiment, an 8” inch wellbore simulator, with 100 ft length, with 4 ½” inch drill-pipe was used. During the work, the following variables were taken into the consideration: rotary speed, hole inclination, mud rheology, cuttings size, and fluid flow rate. Several major conclusions were drawn. First, Sanchez et al. found that drill pipe rotation had a significant effect on the hole cleaning during directional well drilling. This conclusion was rather opposite to previously published results by other researchers. Secondly, it was observed that dynamic behavior of the drill pipe played a major role on the improvements of the hole cleaning. It was noticed that at horizontal wellbore with inclination of 90° degrees, a low flow rate with high rotation of drill pipe (RPM) improved cuttings transport significantly. This study proved that smaller cuttings were more difficult to remove from wellbore. However, with a high rotary speed and high viscosity of mud, it was easier to transport smaller cuttings to surface. It was also shown in the study that benefits of pipe rotation to hole cleaning was mainly a function of rotary speed, hole inclination, flow rate, mud rheology, and cuttings size. According to Sanchez et al., the latter two had the least effect on the cutting transport.

Same year, *Pilehvari et al.*[34] presented an overview of the developments in cuttings transport over the years, the shortcomings of its present status, and recommendations for future research were given. The scientists were focusing on pioneering experimental studies performed in 1986-1991. Further, they reviewed the number of research activities initiated by various oil companies during 1980's. The major part of the presented overview was focused on the empirical approach and models/correlations that were developed from the investigations in 1990 years. At the end of this review, a summary of guidelines were presented for effective hole cleaning.

In 1999, *Kamp* and *Rivero*[4] presented a two-layer numerical simulation model for calculation of cuttings bed heights, pressure drop and cuttings transport velocities at different rate of penetration and mudflow rates. The results of the study were compared with the correlation-based model (based on experimental data) that had been published earlier by Larsen[3]. It was shown that the model gave good quantitative predictions in comparison with a correlation-based model. However, the presented model over-predicted cuttings transport at given flow rates.

In 1999, *Rubiandini* [5] developed an empirical model for estimating mud minimum velocity for cuttings transport in vertical and horizontal well. In his work, Rudi Rubiandini modified *Moore's*[6] slip velocity for vertical well in such a way that it would be possible to use it for inclined wellbore. In addition, he introduced correction factors by performing regression analysis with data taken from Larsen's model[2] and Peden's[1] experimental data to calculate the minimum transport velocity (Vmin). Rubiandini presented a modified equation to determine the minimum flow velocity needed to transport cuttings to surface in an inclined wellbore. During the equation validation, the important differences between the different models were drawn.

In 2003, *Li* and *Kuru*[35] developed a one-dimension two-phase mechanistic model to simulate cuttings transport with foam in vertical wellbore. The model was solved numerically in order to predict the optimum foam flow rate and rheological properties to maximize the cuttings transport efficiency in the vertical wells. Several conclusions were made. First, model predictions of flowing bottomhole pressure for foam flow were in a sufficient agreement with the field data. Second, several observations on foam quality (that was dependant on phase influx from the reservoir) were made. The effect of the foam quality on the bottomhole pressure was also established. The developed model could be used to write a computer programs for practical design purposes as well as to develop guidelines for field specialists for usage in operational control of cuttings transport with foam.

In 2004, *Yu et al.* [36] performed a study on improving cuttings transport capacity of drilling fluid in a horizontal wellbore by attaching air bubbles to the surface of drilled cuttings by using chemical surfactants. The laboratory experiments were performed in order to determine the effects of chemical surfactants on attachment of air bubbles to cutting particles. The study revealed that the use of certain chemical surfactants could increase the strength of attachments between air bubbles and drilling cuttings. This study proved that this method could stepwise improve cuttings transport capacity in horizontal and inclines wells.

In 2007, *Mirhaj et al.*[37]presented results of an extensive experimental study on model development for cuttings transport in highly deviated wellbores. The experimental part of this study focused on the minimum transport velocity required to carry all the cuttings out of the wellbore. The influence of the following variable was also investigated: flow rate, inclination angle, mud rheological properties and mud weight, cuttings size, drill pipe eccentricity, and ROP. The model was developed based on data collected at inclination angle between 55° and 90° degrees from vertical. The model predictions were compared with experimental results in order to verify the model accuracy.

2.1 Summary of literature review

As directional drilling was more and more adapted by petroleum companies, hole cleaning became one of the major challenges in the industry. It was evident that cuttings transport in inclined and horizontal wellbore was rather complicated matter and required more research for solving this challenge. A lot of studies and experiments were initiated on cuttings transport in 1980's[3,6-11]. By this time, the majority of the scientists were focused on the cuttings transport in the inclined wells[2- 4, 9-17, 19, 24, 26-28, 31, 33, 34, 36, 37]. However, some established experimental studies were directed on the cuttings transport in the vertical wellbore[6, 8, 21, 35]. However, most of the research on the vertical drilling was done in the 1970's.

The cuttings transport studies are categorized by two main approaches. The first approach is known as the empirical approach. Using this approach, a number of scientists analyzed the drilling parameters[16, 31, 33] and other factors, such as annular flow velocity, apparent viscosity, and particle size[2, 8, 21, 25, 37], to see how they influenced the transportation of the cuttings through the wellbore. Okrajni & Azar[10], Becker et al.[13], Luo et al.[19], Martins et al.[24], Kenny et al.[25] used empirical approach in their research on mud rheology effect and rheological parameters affecting particle settings and hole cleaning. Tomren et al.[9] published their study on the effect of different fluid regimes on cuttings transport, while Locket et al.[18] and Phillip et al.[32] took it further and studied vortices influence on hole cleaning. As new technologies for deviated wells developed, the new types of drilling fluid were introduced and new studies were initiated. Thus, Brown et al.[11] performed analysis on hole cleaning in deviated wells using water and HEC polymers as drilling fluids. Recently, Yu et al.[36] published the results on their experiments that were performed to determine the effects of chemical surfactants on attachment of air bubbles to cutting particles.

Based on experimental studies, the scientists could develop a set of empirical correlations [2, 5, 24, 27], some computer programs[18, 23, 26], and various models [1, 2, 4, 5, 7, 10, 13,14, 17, 22, 25, 28, 29, 36,37]. For example, Peden et al.[1] and Larsen et al.[2] performed a large number of experiments and developed empirical models. Later Rubiandini[5] (1999), based on Moore's[6] vertical slip-velocity model, Larsen's empirical model and Peden's experimental data, developed his own model to calculate minimum fluid flow velocity both in vertical and horizontal wellbores.

The second approach is a theoretical or mechanistic approach. Here, a scientist develops a set of equations by analyzing the forces that are involved in the cuttings transport. These equations are then solved numerically, with certain physical or mathematical assumptions. For instance, Gavignet and Sobey[3] developed a 2-layer model for cuttings transport in an eccentric annulus. Kamp and Rivero[4] used this method for developing a 2-layer numerical simulation model for calculations of cuttings bed various parameters. Martins et al.[15] presented a 2-layer model for cuttings transport in a horizontal wells by using a dimensionless approach. In addition, a two – layer model for prediction for flow patterns and pressure drops was presented by Doron and Barnea[17]. A three-layer model was presented by Nguyen and Rahman[28]. Few years later, Doron et al.[29] extended the two-layer model into three-layer model in order to account for the angle of inclination. Recently, Li and Kuru[35] presented a one-dimension two-phase mechanistic model to simulate cuttings transport with foam in vertical wellbore.

Despite the large number of the models that had been produced using these two approaches, some of the models needed further development[20, 25, 27, 35]. However, a few models have been presented by combining the theory and best-known practice (Larsen’s model, chapter 4) and by modifying previous model and empirical correlations (Rubiandini’s model, chapter 6).

3. BASIC THEORY AND EQUATIONS

The unknown concepts and parameters used in the previous chapter are explained in this chapter.

One of the drilling mud's main functions is to lift the cutting from bottom hole to the surface. Hence, it is necessary to analyze the cuttings transport mechanism and the factors that affect the cutting transport in vertical and horizontal wells.

During drilling operation, drillings fluid has several functions, and these functions are as follows:

- Transport of cutting to the surface;
- When the mud pump is turned off during connections, drillings fluid provides a suspension system for cuttings and weight material in the mud and prevents cuttings to fall down in the lower part of annulus;
- Mud cake build-up around a wellbore to prevent inflow of formation fluid in to well;
- Control of formation pressure;
- Cool down and lubricate drill bit and string;
- Buoyancy effect on drill pipe and casing;
- Send logging information to the surface during drilling.

Most of the definitions are taken from API publication[38]. In this chapter, drilling fluid rheological parameters, such as viscosity, density, shear stress, and shear rate, are explained. In addition, some concepts like flow regimes, Newtonian and Non-Newtonian fluids, Bingham plastic model and power law model are defined. The nomenclature is provided at the end of this chapter.

3. 1 Flow regimes

The flow regime has a direct impact on the cuttings transport, and the flow can be either laminar or turbulent. The flow regime is dependent on the fluid velocity, size, and shape of the annulus, fluid density, and viscosity[38]. The fluid flow region between laminar and turbulent is known as a transition region. In this region, the fluid has both laminar and turbulent characteristics. During drilling, rotation of drill-pipe can create a turbulent flow. When flow velocity is low or when the fluid has high viscosity, it creates a laminar flow. On contrary, the turbulent flow arises when the flow velocity is high or when the fluid has low viscosity. In addition, drill pipe or wall roughness will increase the flow turbulence. In general, it requires a higher pump pressure to transport fluid in turbulent flow than in laminar flow.

The transition region between laminar and turbulent flow is controlled by viscous forces and inertial forces in the flow. In the laminar flow, the viscous forces are dominant, while in the turbulent flow the inertial forces are most important. The ratio of inertial forces to viscous forces is known as the Reynolds number. The dimensionless Reynolds number in the annulus is defined as follows[38]:

$$Re = \frac{(D_{hole-}D_{pipe})*V*\rho}{\mu} \text{ ....}(3.1.1)$$

The transition from laminar to turbulent flow regime occurs at a critical flow velocity. For a typical drilling fluid, the Reynolds number in the transition region is varying between 2000 and 4000.

3. 2 Shear Stress

Shear stress is the force required to maintain a particular rate of fluid flow, and is measured as a force per unit area. The shear stress is defined as follows[38]:

$$\tau = \frac{F}{A} \text{ ....}(3.2.1)$$

In order to calculate shear stress in the annulus, the force that pushes fluid through annulus and the area of the fluid surface in the annulus is calculated as follows[38]:

$$F = P * \pi \frac{D_{hole}^2 - D_{pipe}^2}{4} \text{..}(3.\ 2.2)$$

Equation for surface area in the annulus subjected to stress is defined by following[38]:

$$A = \pi * L\left[D_{hole} + D_{pipe}\right] \text{ ....}(3.\ 2.3)$$

With use of equations (3.2.2) and (3. 2.3), it is possible to calculate shear stress (3. 2.1) in the annulus.

3.3 Shear Rate

Shear rate is defined as the velocity gradient measured across the diameter of an annulus. The velocity gradient can be expressed as the rate of velocity changes with distance from hole wall.
Shear rate can be expressed mathematically as follows[38]:

$$\gamma = \frac{\Delta V}{\Delta r} \text{.. }(3.3.1)$$

The shear rate at the annulus wall for a Newtonian fluid is defined as follows[38]:

$$\gamma_a = \frac{12*V_a}{D_{hole-}\ D_{pipe}} \text{ ....}(3.3.2)$$

The average velocity in the annulus (V_a) is expressed as follows[38]:

$$V_a = \frac{4Q}{\pi[D_{hole}^2 - D_{pipe}^2]} \quad \text{……(3.3.3)}$$

During drilling, density of drilled cuttings is higher than the drilling-fluid, and it leads to cuttings particle settling in a drilling fluid. The fluid that surrounds particles is subjected to a shear rate, which is known as settling shear rate (γ_s)[38]:

$$\gamma_s = \frac{12 * V_s}{D_{cuttings}} \quad \text{……(3.3.4)}$$

3. 4 Viscosity and Apparent Viscosity

The viscosity is defined as the ratio of shear stress to shear rate[38]. Unit for the viscosity is dyne-s/cm^2, which is represented as Poise (P). 1 Poise represents a relatively high viscosity for most fluids, and therefore unit centi-Poise (cP) is more often used.
The equation for viscosity is defined as follows[38]:

$$\mu = \frac{\tau}{\gamma} \quad \text{……(3.4.1)}$$

Viscosity varies for most drilling fluids, and it varies with shear rate.

Apparent viscosity is defined as a viscosity of a fluid measured at a given shear rate at a fixed temperature[39]. In addition, apparent viscosity is a rheological property calculated from rheometer reading performed on drilling fluid. In order for a viscosity measurement to be meaningful, the shear rate must be stated or defined.

The apparent viscosity is expressed as[39]:

$$\mu_a = pv + \frac{5YP(D_{hole} - D_{pipe})}{V_{crit}} \quad \text{……(3.4.2)}$$

3. 5 Newtonian and Non-Newtonian fluids

Drilling fluids are classified by their rheological behavior. The fluids with constant viscosity when shear rate is changing are called as Newtonian fluids[38], for example water. Shear stress in Newtonian fluid is directly proportional to shear rate (figure 3.5). On the other hand, if the share rate changes, viscosity for the Non-Newtonian fluids changes as well. In the Non-Newtonian fluids, shear stress is not directly proportional to shear rate. Most drilling fluids are Non-Newtonian fluids. Both temperature and pressure can influence the viscosity of these drilling fluids.
The majority of drilling fluids have shear-thinning capability. That means that viscosity of these drilling fluids is lower at higher shear rate than at lower shear rate.

To define the difference between Newtonian and Non-Newtonian fluids, an API standard concentric-cylinder viscometer is used. When the 600-rpm readings value is two times higher' than 300-rpm reading value, then the fluid has Newtonian behavior. On the other hand, when the 600-rpm readings value is less than two times of the 300-rpm reading value, the fluid has Non-Newtonian and shear thinning behavior.

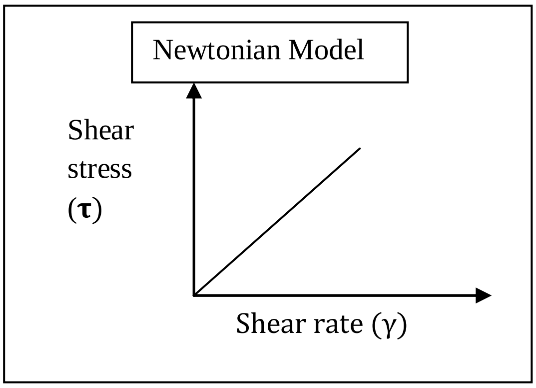


Figure (3.5): Newtonian Fluid Model (Modified from www. glossary. oilfield. slb.com)

3. 6 Concentric-cylinder viscometer

Atmospheric concentric-cylinder viscometer is commonly used for testing drilling fluid. In concentric-cylinder viscometer, drilling fluid is contained in the annular space between two cylinders[38]. The outer rotor is rotated with a constant rotational velocity, usually powered by electric motor (figure 3.6). The rotation of the rotor in the drilling fluid produces a torque in the inner cylinder. The torque on the inner cylinder is usually measured with a torsion spring. Then the plastic viscosity and yield point can be directly read from rotor speeds in different rpm.

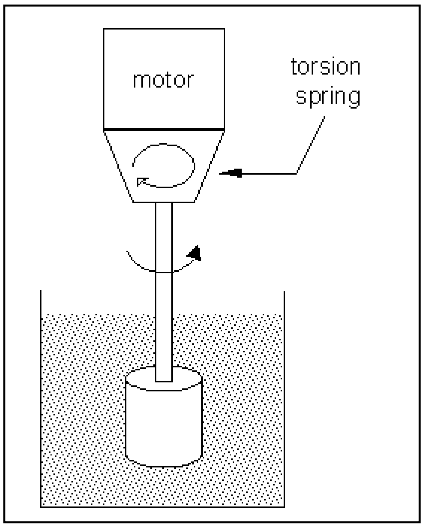


Figure (3.6): Schematic diagram of viscometer

3.7 Rheological models

The determination of drilling fluid rheological parameters is important for better understanding of hole cleaning efficiency. Rheological models are used to provide assistance in characterization of fluid flow[38]. To have a better understanding of fluid performance, the knowledge of rheological models combined with practical experience is necessary.

The temperature and pressure changes in the well change the rheology parameters, and it must be takes into account. At high temperature (e.g.150°C), the viscosity of drilling fluid decreases, and at the low temperature (e.g. 21°C), the viscosity of drilling fluid increases. On the other hand, increase in pressure leads to viscosity increase of the drilling fluid. The effect of the temperature and pressure on the drilling fluid viscosity is non-linear.

3. 8 Density

Temperature and pressure changes in the bottomhole can affect the drilling fluids density[38]. At low temperature, the density of drilling fluid increases and at the high temperature, the density of the drilling fluids decreases. The effects of temperature on the density of the drilling fluids are near linear. On the other hand, pressure increase makes the density of the drilling fluid increase and this effect is generally non-linear. The effect of the pressure and temperature on the density of the water based drilling fluid is usually week.

3. 9 Bingham Plastic Model

Two parameters, plastic viscosity (PV) and yield point (YP) are used in the Bingham plastic rheology model.
The equation for Bingham plastic model is defined as[39]:

$$\boldsymbol{\tau = YP + PV * (\gamma)} \quad \text{.......................................(3.9.1)}$$

This model characterizes fluids in the high shear rate region. Bingham model describes fluids in the way that shear stress ratio versus shear rate ratio is linear (figure 3.9). Plastic viscosity is the slope of the shear stress versus shear rate line above the yield point (YP) and yield point is the threshold stress. During drilling with high ROP, the plastic viscosity should be kept as low as possible, and it can be obtained by minimizing solid particles in size as small as two microns that corresponding to a spherical diameter, called Colloidal Solids.
Yet, yield point must be high enough to transport cuttings out of the hole, but not very large since it creates a large pump pressure during circulation.

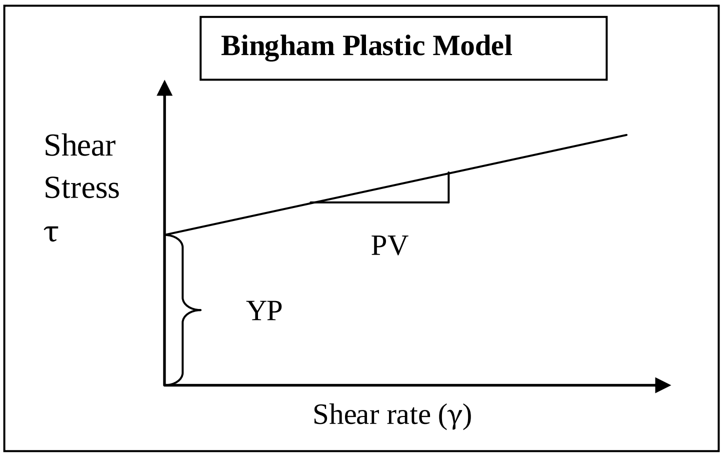


Figure (3.9): Bingham Plastic Model (Modified from www.glossary.oilfield.slb.com)

3. 10 Power law Model

Power law model (figure 3.10), is used to describe the flow of shear thinning or pseudo-plastic drilling fluids. A power law fluid is a type of Newtonian fluid, where the shear stress is given by following[40]:

$$\boldsymbol{\tau = k_p * \dot{\gamma}^n} \quad \text{..........} (3.10.1)$$

Power law fluid is divided into three different types, depending of flow behavior index (n):

- n < 1 → Pseudo-plastic
- n = 1 → Newtonian fluid
- n > 1 → Dilatant (less common)

The “n” value (flow behavior index) cannot be zero.

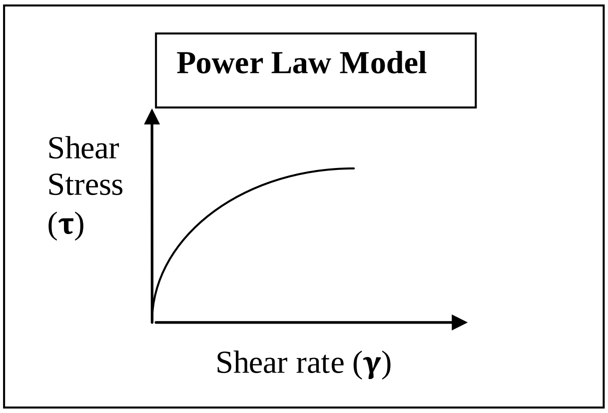


Figure (3.10): Power Law Model (Modified from www.glossary.oilfield.slb.com)

3. 11 Herschel-Bulkley Model

The Herschel-Bulkley model (figure 3.11) is also called the modified power law and yield pseudo-plastic model[38]. This model describes the flow of pseudo-plastic drilling fluids that requires a yield stress to initiate flow. This model is widely used since it describes the flow behavior of most drilling fluids. The equation of Herschel-Bulkley model includes a yield stress value, which is important for several hydraulics issues. Moreover, Herschel-Bulkley model is considered as a unifying model, which can fit both Bingham plastic fluids and power law fluids, and everything else in between. The equation for Herschel-Bulkley model can be presented as follows:

$$\boldsymbol{\tau = \tau_y + k_h * \gamma^n} \quad \text{..........} (3.11.1)$$

In the Herschel-Bulkley equation, the flow index (n) is equal to one, if the yield stress is equal to yield point, then Herschel-Bulkley equation reduces to a Bingham plastic model.

When the yield stress is zero, the Herschel-Bulkley equation reduces to a Power law model.

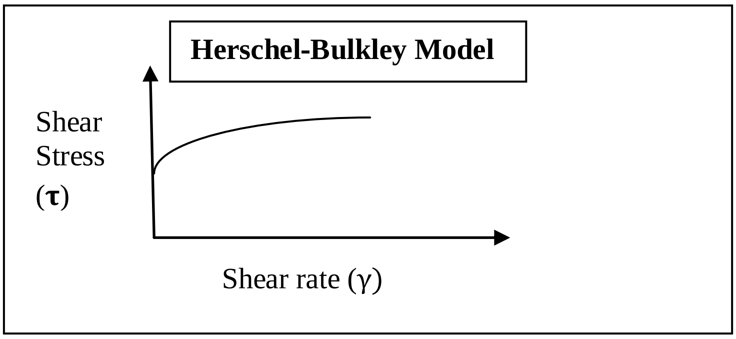


Figure 3.11: Herschel-Bulkley Model (Modified from www.glossary.oilfield.slb.com)

3. 12 Effect of annular eccentricity in cuttings transport

During drilling, drill-pipe is usually not concentric in the hole; i.e. drill pipe is not located in the center of the annulus (figure 3.12.2). This is especially the case for inclined and horizontal wellbores, where pipe weight forces pipe to lay against the hole. The definition of eccentricity is expressed in terms of dimensionless (ϵ) and is equal to[7]:

$$\boldsymbol{\epsilon = \frac{2e}{d_h} = \frac{2e}{d_{o-d_i}}} \text{ ....} (3.12.1)$$

In a concentric annulus, $e = 0$, and thus, $\epsilon = 0$ in equation (3.12.1).

In a fully eccentric annulus, where the inner pipe is in contact with the outer pipe, $e = r_o - r_i$ and $\epsilon = 1$.

Iyoho and Azar[7] defined positive and negative eccentricity as pipe displacement towards the low side and high side of the hole, respectively.

The figures below show the concentric and eccentric annuli:

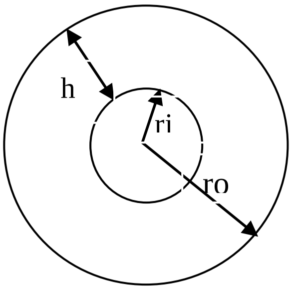


Figure (3.12.1): Concentric annuli, where **h** is constant (Modified from Iyoho and Azar[7])

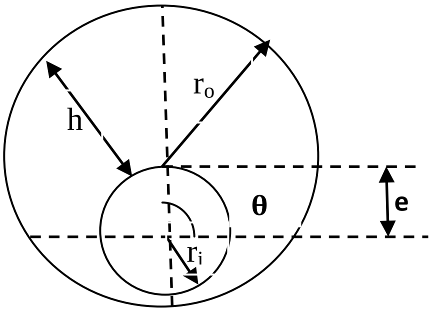


Figure (3.12.2): Eccentric annuli, where **h** is not constant (Modified from Iyoho and Azar[7])

3. 13 Cuttings transport in vertical and near-vertical wells

Hole cleaning in vertical wells is usually defined by comparing the annular fluid velocity with the cuttings slip velocity[38]. If the annular flow velocity is higher than the cuttings slip velocity, then all cuttings will transported up to surface. There are several models. Here, the model given in API publication[38] is presented.

The in-situ cuttings concentration (C_a), can be calculated as follows[38]:

$$C_a = \frac{D_b^2 * ROP}{448.4 * Q * R_t} \tag{3.13.1}$$

Cuttings transport ratio (R_t) can be calculated as follows[38]:

$$R_t = \frac{V_u}{V_a} = \frac{V_a - V_s}{V_a} \tag{3.13.2}$$

The cuttings Reynolds numbers can be calculated as follows[38]:

$$Re = \frac{928 * \rho * V_s * D_c}{\mu_a} \tag{3.13.3}$$

When the Reynolds number is larger than 100, cuttings flow regime is turbulent, and cuttings slip velocity (in turbulent flow) can be calculated as follows[38]:

$$V_s = 2.19 \left[\frac{h_c(\rho_c - \rho)}{\rho}\right]^{1/2} \tag{3.13.4}$$

The symbol (h_c) in equation (3.13.4) indicates cuttings height.

When the Reynolds number is lower than 100, the flow is assumed to be laminar, and cuttings slip velocity (in laminar flow) can be calculated as follows[38]:

$$V_s = 0.0203 * \tau_s \left[\frac{D_c * \gamma}{\rho^{1/2}}\right]^{1/2} \tag{3.13.5}$$

Equation (3.13.5) indicates that cuttings slip velocity (V_s) increases when the cuttings diameter (D_c) increases.

The shear rate due to cuttings slip in equations (3.13.5) can be calculated as follows[38]:

$$\tau_s = 7.9[h_c * (8.345 * \rho_c - \rho)]^{1/2} \tag{3.13.6}$$

During drilling, three parameters are important for hole cleaning, namely drilling fluid density, viscosity, and annular flow velocity. By increasing any of these variables, the hole cleaning will improve.

In a vertical wellbore, a carrying capacity index can be used to describe hole cleaning. The carrying capacity index is defined as[38]:

$$\boldsymbol{CCI = \frac{\rho * k_1 * V_a}{400{,}000}} \quad \text{..........}(3.13.7)$$

The “k_1” value in equation (3.13.7) is carrying capacity index in a power law model. The “k_1” and the “n” value in power law equation is calculated as follows[38]:

$$\boldsymbol{k_1 = 511^{(1-n_p)} * [PV + YP]} \quad \text{..........}(3.13.8)$$

$$\boldsymbol{n_p = 3.32 * log_{10} \frac{2 * PV + YP}{PV + YP}} \quad \text{..........}(3.13.9)$$

When the carrying capacity index (CCI) is equal to one or greater than one, it is an evidence for a good hole cleaning. Then, cutting size is usually large and has a sharp shape. On the contrary, when carrying capacity index has a value of 0.5, the cuttings size is generally small and has a rounded shape. When carrying capacity index has a value of 0.3, the cuttings are of grain size[38].

Nomenclature for chapter 3

- A = Surface area, ($inch^2$), (m^2)
- C_a = In-situ cuttings volume concentration, (dimensionless)
- D_b = Bit diameter, (inch), (m)
- D_c = $D_{cuttings}$= Cuttings diameter, (inch), (m)
- D_{hole} = Hole diameter, (inch), (m)
- D_{pipe} = Drill-pipe diameter, (inch), (m)
- d_o = Outer pipe diameter, (inch), (mm)
- d_i = Inner pipe diameter, (inch), (m)
- d_h = Hydraulic diameter, or casing inside diameter, (inch), (mm)
- e = Inner pipe offset relative to hole center, (inch), (mm)
- F = Force, (lb_f), (N)
- h = local annulus clearance or slot height, (in), (m)
- h_c = Cuttings height, (inch), (m)
- k_1 = Power law viscosity, (cP), (Pa*s)
- k_h = Consistency factor (Herschel-Bulkley fluids), (lb_f*S^n/ ft^2), (Pa*s^n)
- k_p = Consistency factor (Power-law fluids), (lb_f*S^n/ ft^2), (Pa*s^n)
- L = Length of annulus, (inch), (m)
- n = Flow index, (dimensionless)
- n_p = Flow behavior index (power-law fluids), (dimensionless)
- P = Pressure on the end of liquid column, (lb_f/jn^2), (kPa)
- PV = Plastic Viscosity, (cP), (Pa*s)
- Q = Volumetric flow rate, (gal/min), (m^3/s)
- R_t = Transport Ratio, (dimensionless)
- ROP = Rate of penetration, (ft/h), (m/h)
- V = Flow velocity, (ft/min), (m/s)
- V_a = Average velocity in annulus, (ft/min), (m/s)
- V_{crit} = Critical viscosity, (ft/min,), (m/s)
- V_s = V_{slip}= Slip velocity of cuttings, (ft/min), (m/s)
- V_u = Cuttings net upward velocity, (ft/min), (m/s)
- YP = Yield point, (lb_f/100 ft^2), (Pa)
- γ = Shear Rate, (s^{-1})
- γ_a = Share rate at annulus wall for a Newtonian fluid, (s^{-1})
- γ_s = Cuttings settling shear rate, (s^{-1})
- $\boldsymbol{\dot{\gamma}^n} =$ Shear rate, (S^{-1})
- Δr = Distance between fluid layers, (inch), (m)
- ΔV = Velocity change between fluid layers, (ft/min), (m/s)
- μ = Fluid viscosity, (cP), (Pa*s)
- μ_a = Apparent Viscosity, (cP), (Pa*s)
- ρ = Fluid density, (lb_m/gal), (kg/m^3)
- ρ_c = Density of cuttings, (lb_m/gal), (kg/m^3), (g/cm3)
- ϵ = Pipe/hole eccentricity, (%)
- τ = Shear Stress, (lb_f/100 ft^2), (Pa)
- τ_y = Yield stress, (lb_f/100 ft^2), (Pa)

4. LARSEN'S MODEL

In this chapter, an example of an empirical model that was described by Larsen et al.[2] is presented. During the extensive experimental study, Larsen et al. focused on cuttings size, angle of inclination and mud weight, and therefore were able to develop empirical correlations for these variables. In addition, a design model was developed to predict the critical transport fluid velocity, equivalent slip velocity, and critical velocity. This chapter is based on Larsen et al.[2] publication. The nomenclature is provided at the end of this chapter. Matlab codes that were used to draw graphs that are illustrated in this chapter are presented in Appendix A.

4. 1 Experimental data set

The experiment was performed in a pipe with a 5.0" inside diameter, and a drill-pipe with 2,375" outside diameter and length of 35 ft. In this experiment, drill-pipe eccentricity varied from negative (-62%) to positive (+62%). During the experiment, cuttings were injected at three different rates, namely 10, 20, and 30 lbm/min that corresponded to ROP of 27, 54, and 81 (ft/hr) (equation 4.2.5). Although the effect of rpm was studied during this research, it was negligible for various parameters. The pipe was rotated at constant speed of 50 rpm throughout the experiment.

4. 2 Larsen's equivalent slip velocity and Critical Transport Fluid Velocity (CTFV)

Larsen et al. defined equivalent slip velocity as a flow velocity difference between cuttings and drilling fluid. Equation for equivalent slip velocity [ESV] (ft/sec) is defined as correction factors for inclination angle, cuttings size, and mud weight multiplied by uncorrected equivalent slip velocity $\overline{\boldsymbol{V}}_{\boldsymbol{slip}}$, and is shown as follows:

$$\boldsymbol{V_{slip} = \overline{V}_{slip} * C_{ang} * C_{size} * C_{mw}} \quad \text{.......} (4.2.1)$$

Larsen and his coworkers defined critical transport fluid velocity (CTFV) as the minimum fluid velocity that is required for keeping a continuously upward movement of the cuttings during circulation. That means that at this velocity or higher, the hole cleaning will be sufficient enough so that no cuttings will accumulate in the lower part of the wellbore.

The equation for critical transport fluid velocity (CTFV or V_{crit}) is the sum of cuttings transport velocity (CTV or V_{cut}) and slip velocity (V_{slip}):

$$\boldsymbol{V_{crit} = V_{cut} + V_{slip}} \quad \text{.......} (4.2.2)$$

Cuttings transport velocity (CTV or V_{cut}) can be expressed through a simple mass balance equation:

Mass generated by drill bit= Mass transported by Mud

$$\boldsymbol{\rho_{cut} * Q_{inj} = V_{cut} * A_{open} * C_{conc-ft} * \rho_{cut}} \quad \text{.......} (4.2.3)$$

Cuttings transport velocity in equation (4.2.2) is calculated by:

$$\boldsymbol{V_{cut}} = \frac{\boldsymbol{Q_{inj}}}{\boldsymbol{A_{open}} * \boldsymbol{C_{conc-fr}}} \quad \text{.......................................} (4.2.4)$$

In order to convert volumetric injection rate (Qinj) to ROP, the following equation has been used:

$$\boldsymbol{ROP\left(\frac{ft}{hrs}\right) = Q_{inj}\left(\frac{ft}{sec}\right) * \left(\frac{3600sec}{1hrs}\right)\left(\frac{1}{A_{hole}(ft^2)}\right)} \quad \text{.......................................} (4.2.5)$$

By substituting volumetric injection ratio (Q_{inj}) in equation (4.2.4) with ROP in equation (4.2.5), it is possible to calculate cuttings transport velocity considering ROP, drill-pipe, hole diameter, and fractional cuttings concentration:

$$\boldsymbol{V_{cut}} = \frac{\boldsymbol{ROP}}{\boldsymbol{36\left[1-\left(\frac{A_{pipe}}{A_{hole}}\right)\right]C_{conc}}} \quad \text{.......................................} (4.2.6)$$

or

$$\boldsymbol{V_{cut}} = \frac{\boldsymbol{ROP}}{\boldsymbol{36\left[1-\left(\frac{D_{pipe}}{D_{hole}}\right)^2\right]C_{conc}}} \quad \text{.......................................} (4.2.7)$$

Uncorrected equivalent slip velocity $\boldsymbol{\overline{V}_{slip}}$ in equation (4.2.1), based on experimental data, can be calculated as follows:

$$\boldsymbol{\overline{V}_{slip}} \boldsymbol{=0{,}00516*\mu_a+3{,}006} \quad \boldsymbol{For\ \mu_a}<53\ \boldsymbol{cp} \quad \text{.......................................} (4.2.8)$$

$$\boldsymbol{\overline{V}_{slip}} \boldsymbol{=0{,}02554*(\mu_a-53)+3{,}28} \quad \boldsymbol{For\ \mu_a}>53\ cp \quad \text{.......................................} (4.2.9)$$

The apparent viscosity (μ_a) in equations (4.5.1) and (4.5.2) is calculated by:

$$\boldsymbol{\mu_a = pv + \frac{5YP(D_{hole}-D_{pipe})}{V_{crit}}} \quad \text{.......................................} (4.2.10)$$

4. 3 Larsen’s estimated cuttings concentration in annulus

From experimental investigation, Larsen’s et al. developed an equation for annular cuttings concentration, at critical transport fluid velocity, for inclination angles from 55° to 90° degrees:

$$\boldsymbol{C_{conc} = 0{,}01778 * ROP + 0{,}505} \quad \text{.......................................} (4.3.1)$$

By combining equations (4.2.7) and (4.3.1), the cuttings transport velocity (CTV or V_{cut}) is given by:

$$\boldsymbol{V_{cut}} = \frac{\boldsymbol{ROP}}{\boldsymbol{36\left[1-\left(\frac{D_{pipe}}{D_{hole}}\right)^2\right]\left[0{,}64+\frac{18{,}16}{ROP}\right]}} \quad \text{.......................................} (4.3.2)$$

Equation (4.3.2) indicates that cuttings transport velocity (CTV), at a flow rate equal to critical transport fluid velocity (CTFV), is not affected by mud rheology, mud weight, or angle of inclination.

By using MatLab data program, an estimate of cuttings concentration in annulus is expressed as a function of ROP, with value interval between 0 and 120 (ft/hrs):

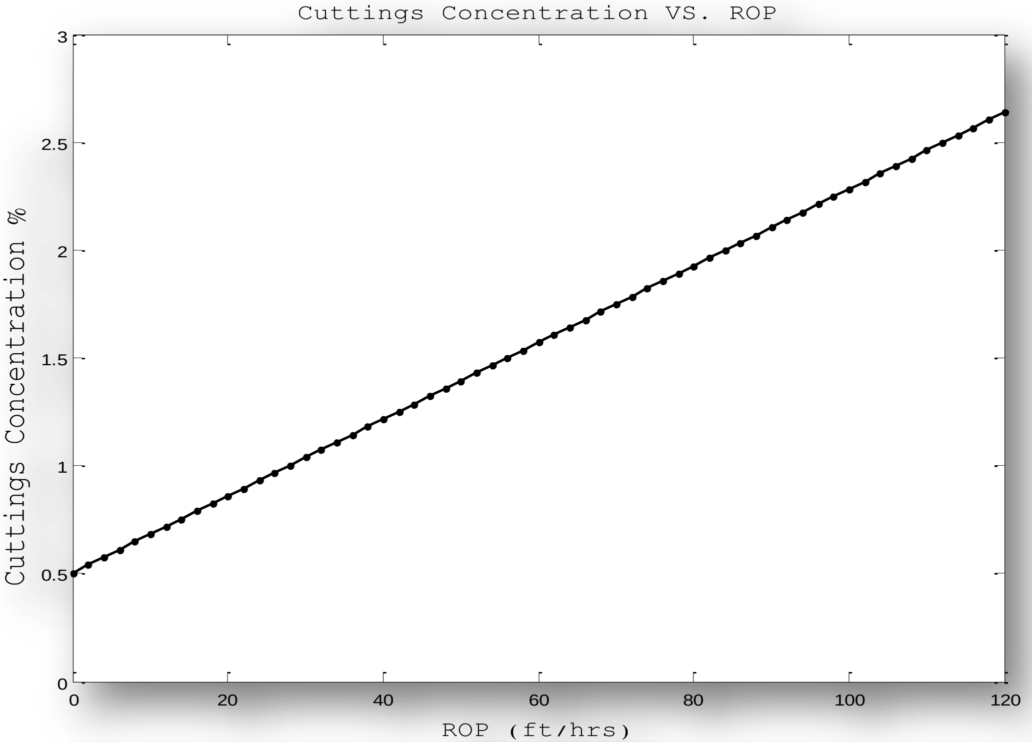


Figure (4.3): Cuttings concentration in annulus versus ROP

The graph in the figure (4.3) shows that cuttings concentration in annulus increases when rate of penetration increases.

4. 4 Larsen's correction factor for inclination

Random angles, namely 55°, 65°, 75°, and 90°, were selected to define the angle of inclination correction factor. Then an average of these angles was found and mean of critical transport flow velocity (CTFV) for these individual angles was calculated. Thus, the angle of inclination correction factor was defined by dividing CTFV mean by angle average.
Correction factor for inclination is calculated by the following expression:

$$\boldsymbol{C_{ang} = 0,0342\theta_{ang} - 0,000233\theta_{ang}^2 - 0,213} \quad \text{...(4.4.1)}$$

By using equation for correction factor for inclination (4.4.1), it is possible to illustrate the inclination angle correction factor, varying from 55° to 90° degrees as a graph:

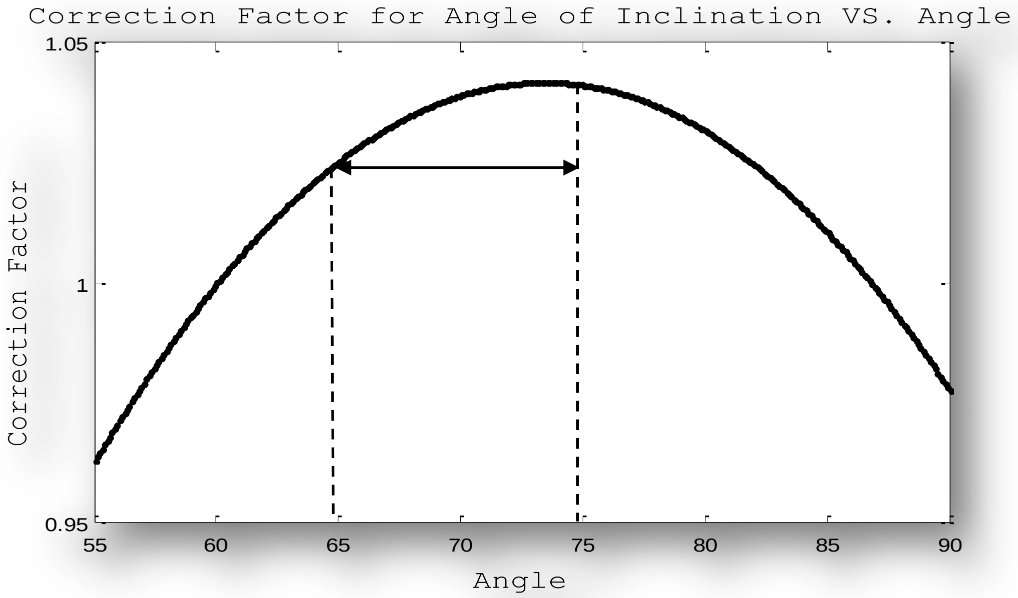


Figure (4.4): Correction factor for angle of inclination between 55°and 90° degrees

The graph (4.4) indicates that in the angle interval from 65° to 75° degrees, it is difficult to establish effective hole cleaning.

4. 5 Larsen's Correction factor for Cuttings Size

In the Larsen's model, three different cuttings sizes were used and therefore, three different bed porosities were established:

Cuttings size (inch)	Rock Type	Shape	Grain Density (gm/cc)	Bed Porosity (%)
Large (0,275")	Limestone	Angular	2,57	41
Medium (0,175")	Limestone	Angular	2,57	36
Small (0,09")	Sand	Round	2,6	39

Table (4.5): Cuttings size and porosity of cuttings bed

The cuttings size correction factor is expressed by:

$$\boldsymbol{C_{size} = -1,04 * D_{Cuttings} + 1,286} \quad \text{...(4.5.1)}$$

By using table (4.5) and equation (4.5.1), the following graph is drawn for cuttings size correction factor:

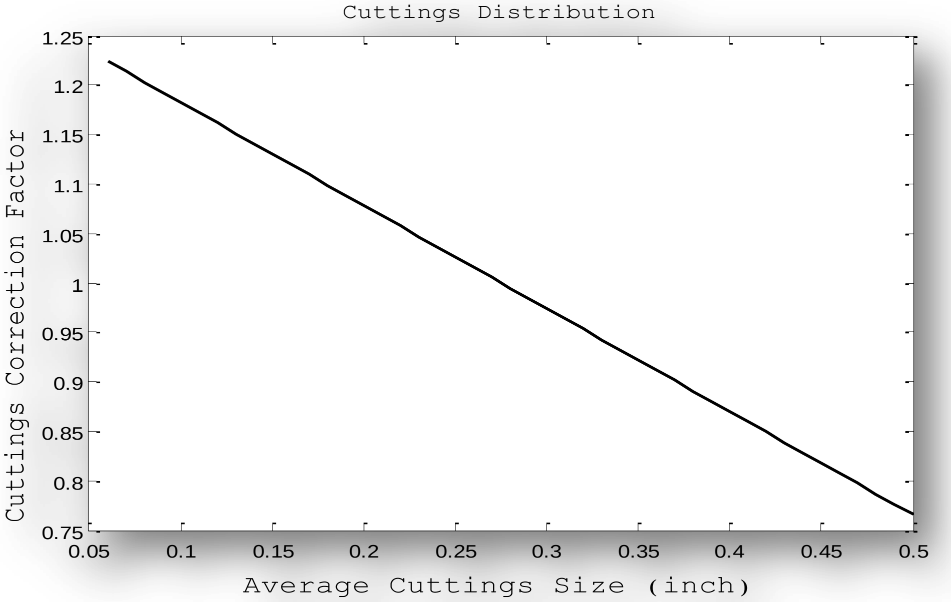


Figure (4.5.1): Cuttings size correlation factor versus cuttings size

This graph illustrates that smaller cuttings give larger cuttings correction factor values (C_{size}) and larger cuttings give smaller cuttings correction factor values. Therefore, by combining this observation with equation (4.2.1), the following can be stated: larger cuttings produce low slip velocity and smaller cuttings produce larger slip velocity.

4. 6 Larsen's Correction factor for Mud Weight

In this experiment Larsen et al., used five different mud types:

	Mud 1	**Mud 2**	**Mud3**	**Mud 4**	**Mud 5**
YP ($1bf/100ft^2$)	6 to 8	14 to 16	24 to 26	14 to 16	14 to 16
PV(cp)	7 to 10	13 to 16	24 to 27	15 to 17	27 to 29
Mud weight (lbm/gal)	8,57	8,65	8,7	11,0	15,0

Table (4.6.1): Five different mud types, used in Larsen's experimental model.

Based on experiments, a correction factor for mud weight was developed:

$$C_{mw} = 1 - 0{,}0333(\rho_m - 8{,}7) \qquad \rho_m > 8{,}7 \quad \text{.......}(4.6.1)$$

$$C_{mw} = 1 \qquad \rho_m < 8{,}7 \quad \text{.......}(4.6.2)$$

Using equations (4.6.1) and (4.6.2), a graph for the mud weight correction factor versus mud weight is drawn:

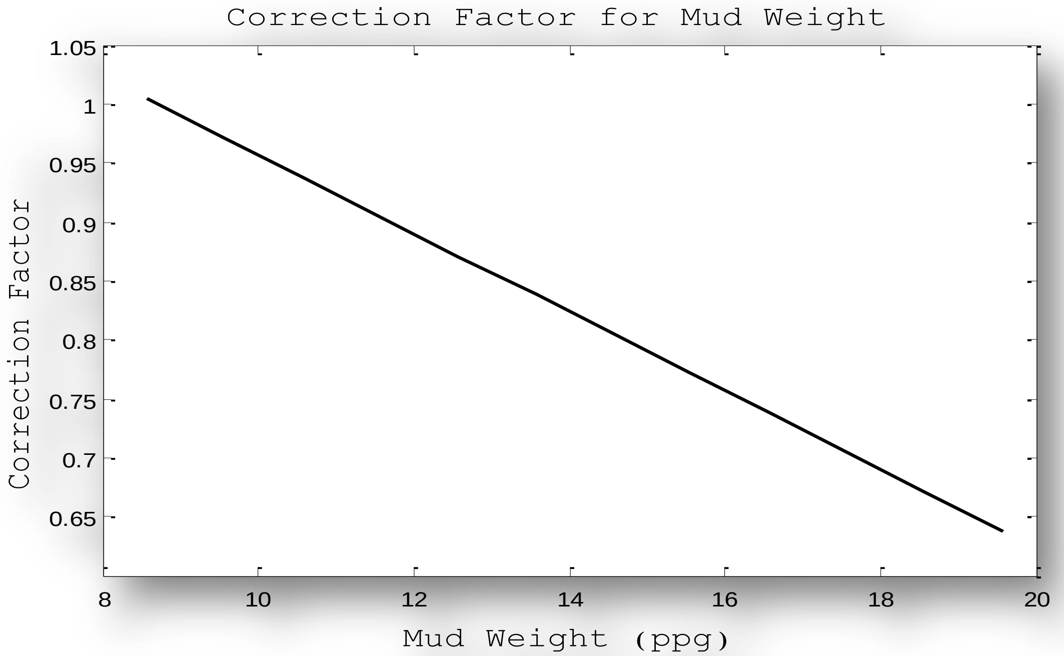


Figure (4.6.1): Correction factor of mud weight versus mud weight (ppg)

This graph shows that correction factor is reduced when the mud weight increases, which mean that higher mud weight reduces slip velocity in equation (4.2.1).

4. 7 Larsen's correction factor for sub-critical fluid flow

Larsen et al. indicated that for any flow velocity that was below critical transport fluid velocity, cuttings would start to accumulate in the wellbore. This fluid velocity was called sub-critical fluid flow. They assumed the velocity in the open area above the accumulation area or above cuttings bed to be equal to critical transport fluid velocity (CTFV).
By neglecting flow through the cuttings bed, the area occupied by cuttings bed is equal to the total annulus area minus the open area above cuttings bed.
Correction factor for cutting concentration at sub-critical fluid flow can be presented as:

$$\boldsymbol{C_{bed} = 0,97 - 0,00231 * \mu_a} \quad \text{..}(4.7)$$

The equation above indicates that cuttings bed concentration is dependent on apparent viscosity and can be graphically expressed as follows:

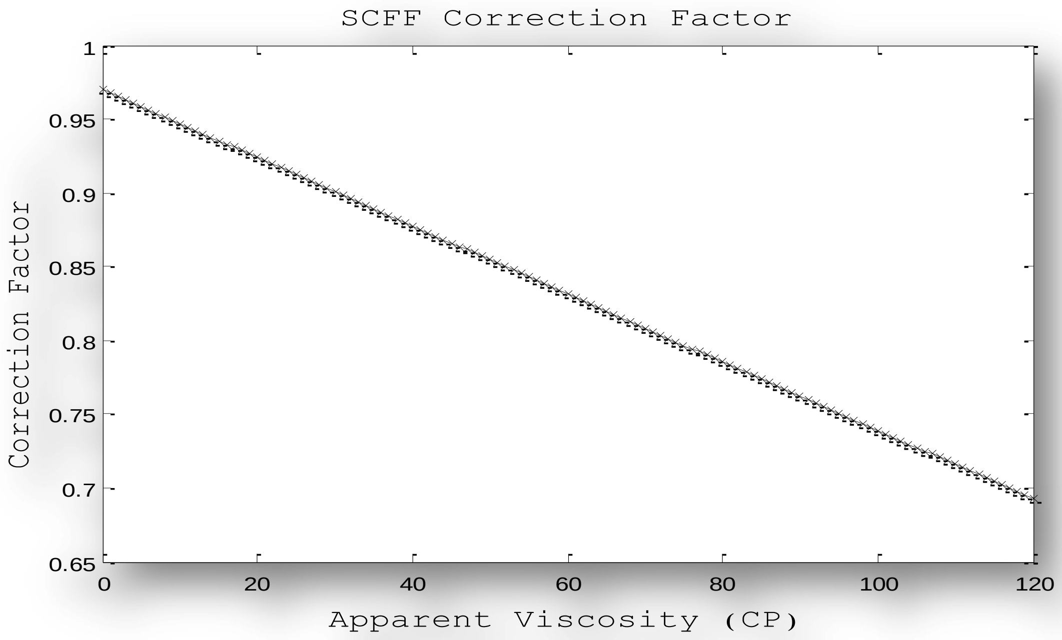
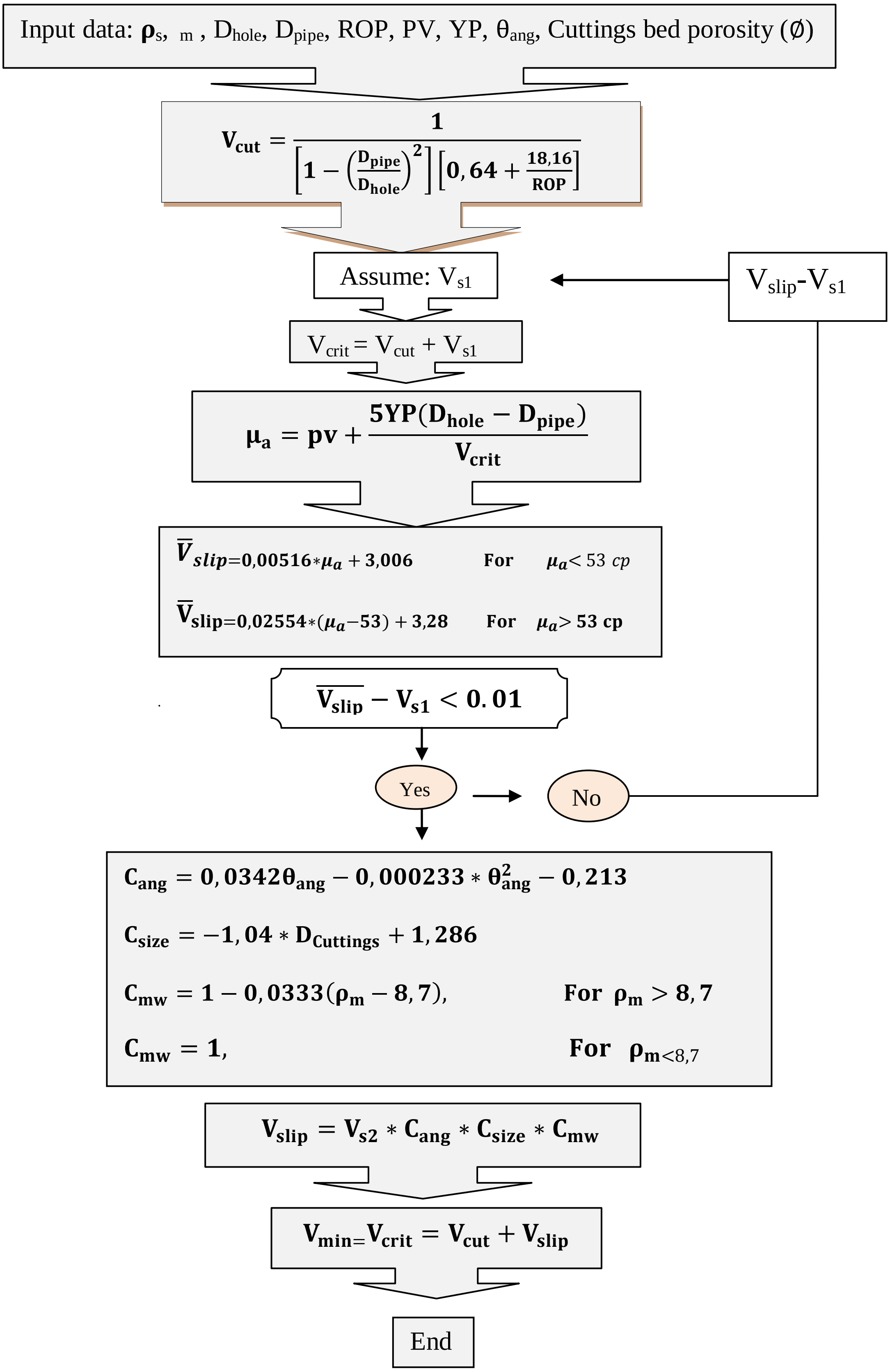


Figure (4.7): Correction factor for cuttings concentration at sub-critical fluid flow

Conclusion: Analysis of the experimental data in the Larsen's model indicates that when the fluid velocity is below critical transport fluid velocity (CTFV), a cuttings bed starts to form and grow in thickness. Larsen et al. discovered that transport of small cuttings size (for ex. 0, 1") was more difficult compared to medium (for ex. 0,175") or large (for ex. 0,275") sized cuttings. Moreover, smaller cuttings required a larger flow rate to reach critical transport flow velocity. From the experimental data, Larsen et al. indicated that a drilling mud with high viscosity required higher flow rate to reach critical transport fluid velocity (CTFV). In addition, in the high angle well, mud with low viscosity had a better effect on the cuttings transport due to presence of the turbulent flow. Larsen et al. observed that angles varying from 65° to 75° were rather difficult to clean. During drilling operation, the flow velocity should be increased to achieve a better cuttings transport, when rate of penetration (ROP) increases. In their study, Larsen et al. considered rpm values. Yet, the results showed that rpm values were negligible for several parameters. During the extensive experimental research, Larsen et al. studied the effect of inclination angle, mud weight, and cuttings size on the cuttings transport flow velocity. By analyzing Larsen's model, it is obvious that Larsen et al., in their experiments, did not consider drill pipe diameter variations or annulus area variations.

4. 8 Larsen’s model in schematic form[5]



Nomenclature for chapter 4

- A_{ann} = Area of annulus (ft^2), (m^2)
- A_{bed} = Area of cuttings bed (ft^2), (m^2)
- A_{open} = Area open to flow above the cuttings bed, (ft^2), (m^2)
- C_{ang} = Correction factor for inclination (dimensionless)
- C_{conc} = Fractional cuttings concentration, by volume, at CTFV (%)
- $C_{conc-ft}$ = Fractional cuttings concentration for a stationary bed corrected for viscosity (dimentionless)
- C_{mw} = Correction factor for mud density (dimensionless)
- C_{size} = Correction factor for cuttings size (dimensionless)
- D_{hole} = Hole diameter (inch), (m)
- D_{pipe} = Drill-pipe diameter (inch), (m)
- PV = Plastic viscosity (cP), (Pa*s)
- Q_{inj} = Volumetric injection rate of cuttings, (ft^3/sec), (m^3/sec)
- ROP = Rate of penetration (ft/hrs), (m/hrs)
- V_{crit} = Critical velocity (CTFV), (ft/sec), (m/sec)
- V_{cut} = Cuttings transport velocity (CTV), (ft/sec), (m/sec)
- V_{slip} = ESV corrected for angl, cuttings size and mud weight (ft/sec), (m/sec)
- $\bar{\boldsymbol{V}}_{\boldsymbol{slip}}$ = Correction factor for slip velocity (dimensionless)
- YP = Yield point (lb_f/100 ft^2), (Pa)
- $\boldsymbol{\mu}_{\boldsymbol{a}}$= Apparent viscosity (cP), (Pa*s)
- $\boldsymbol{\theta}_{\boldsymbol{ang}}$= Angleof inclination of wellbore from vertical (degrees)
- ρ_{cut} = Density of cuttings, (lb_m/gal), (kg/m^3)
- ρ_m = Density of drilling fluid, (lb_m/gal), (kg/m^3)

5. PEDEN'S MODEL

In this chapter, another example of the empirical approach performed by Peden et al.[1] is presented. In this experimental investigation, they focused mainly on forces affecting cuttings transport in inclined wellbore. In addition, the minimum transport velocity concept was introduced and used in this research. This experimental study was one of the series of experiments conducted by Peden and co-workers[12, 26].

5. 1 Concept of Minimum Transport Velocity

Peden et al.[1] presented a empirical model for inclined wellbore that investigated the influence of different variables in cuttings transport, such as hole angle, fluid rheology, cuttings size, drill pipe eccentricity, circulation rate, annular size and pipe rotation, and for this analyses used the concept of minimum transport velocity (MTV).

The MTV method identifies the flow rate in the wellbore, which have capacity for hole cleaning by keeping cuttings rolling or being in full suspension, when flow velocity in annulus is equal or greater than minimum transport velocity (MTV). In this investigation, Peden et al.[1] observed that it was easier to have an effective hole cleaning, when the minimum transport velocity was low.

The hydraulic transport of heterogeneous mixture of drilling fluids and cuttings in the annulus is known for being a complex physical phenomenon. In a slurry flow path, the transport force of cuttings is greater than depositional forces, when the flow velocity in the annulus is high. On contrary, when the flow velocity decreases it results in decrease of turbulent flow intensity, leading to increase of depositional forces on the particles. In this case, cuttings concentration increases in the lower part of the wellbore and at this stage; the cuttings bed is still mobile and moves up in annulus.

For better understanding of cuttings transport mechanism, Peden and his coworkers[1] first analyzed the forces that act on a single cutting when cutting lies down on the lower side of the wellbore. They divided these forces in two groups:

- Depositional forces: Depositional forces can be divided into gravitation force and friction force. Gravitational force makes the cuttings to settle down and to form a bed. Frictional force is a force that acts against cuttings movement and sliding on the surface of the wellbore.
- Transport forces: Transport forces are divided into lift and drag forces. The lifts forces lift up the cuttings and transport them with the flow stream. Lift force arises due to asymmetric distribution of the fluid velocity around the cuttings or by turbulent flow. The drag force rolls the cuttings out of the bed to move them forward.

Depending on the hole angle and the fluid properties, the flow regime of cuttings–liquid mixture in annulus has different flow patterns. These flow patterns are defined as:

- Heterogeneous Suspension: In this flow path, the lift force is stronger than the gravitational force and the cuttings are lifted up and transported in suspension form. However, there is a cuttings concentration gradient across the annulus with more cuttings in the lower part of the annular space. Heterogeneous suspension usually occurs at the high fluid velocity, which produces strong lift force.

- Homogeneous Suspension: Cuttings are transported in suspension and are distributed uniformly over the annular space.

- Suspension/ Saltation or Saltation/ Suspension: In this flow path, cuttings are transported in suspension. However, they are concentrated in the low side of annulus and are transported by jumping forward or saltating on the surface of the low-side wall. In this case, if suspension dominated, it is called Suspension/Saltation and if saltation is dominated, then it is known as Saltation/Suspension.

- Separated moving beds, (Dunes): The separated cuttings bed is formed on the low side of the annulus. In this case, cuttings on the surface of the bed travel forward, while cuttings inside the bed remain stationary. This flow pattern is result of combination of both lift force and drag force. This flow pattern arises when fluid viscosity is low and flow is turbulent. In this case, cuttings bed is transported forward in form of rolling or sliding.

- Continuous moving bed: In this flow pattern, a thin layer of moving bed is created on the low side of the wellbore, and it is only drag force that is strong enough to drag the cuttings forward. Continuous moving bed occurs when fluid viscosity is high and the flow regime is laminar.

- Cuttings Clusters: All cuttings transported in suspension, but cuttings transported in cluster and all of cuttings in the each cluster transported with the same velocity.

- Stationary bed: A continuous cuttings bed is formed in the lower side of the annulus. In this flow pattern, drilling cuttings on the surface of the bed are transported forward in form of rolling or sliding, while the cuttings inside the bed are stationary.

5. 2 Transport of cuttings in suspension and rolling condition

Peden et al.[1] indicated two specific cuttings transport mechanisms that depend on the flow velocity.

- Minimum transport velocity for cuttings rolling: The minimum transport velocity required to roll or slide the cuttings along the lower sidewall of the wellbore.

- Minimum transport velocity for cuttings suspension: The minimum transport velocity required for all cuttings to be suspended in the drilling fluid and transported as a slurry flow path.

For transport of cuttings in suspension form, cuttings lifting force (F_L) must be greater than gravitation force when it is perpendicular to the hole axis (F_{gva}).

For transport of cuttings in rolling form in a moving bed, then drag force (F_D) must be greater than the gravitation force, when it is parallel to hole axis (F_{ga}).

There are only two forces that act on the drilling cuttings in a vertical wellbore, namely the gravitation force and the fluid drag force. For cuttings to be transported out of the well hole, the drag force must be greater than the gravitational force.

5. 3 Experimental results

The results from this experimental investigating[1] indicated that hole inclination had the major effect on the minimum transport velocity (MTV). Transporting cuttings in the rolling form required lower flow velocity compared to transport cuttings in suspension form. Minimum transport velocity required to transport cuttings in the suspension form was less dependent on the fluid rheological properties than transporting them in the rolling form. Peden et al.[1] observed that smaller concentric annuli demanded a lower MTV for hole cleaning than larger one, and turbulent flow regime in the annulus had a significant effect on the hole cleaning. According to Peden et al.[1], it was a high viscosity fluid that was best for effective hole cleaning and transport cuttings in the suspension form. Low and medium viscosity fluids were effective for cuttings transport, respectively. Changing drilling fluid viscosity from medium to high viscosity resulted in lower minimum transport velocity that was an advantage. The experiment showed that pipe rotation had a dramatic improvement on the cuttings transport in the smaller annulus. However, pipe rotation had no significant effect on the hole cleaning in the large annuli pipe. Peden et al.[1] observed that smaller cuttings were transported more effectively in both horizontal and vertical well with use of a low viscosity drilling fluid. On the other hand, larger cuttings were transported more effectively with use of high viscosity drilling fluid. At last, Peden et al. noticed that the highest minimum transport velocity was in angle inclination between 40° to 60° degrees, and this interval was the worst interval for hole cleaning.

Figure (5.3) below shows forces acting on the cuttings when cuttings lay down on the low - side of the wellbore:

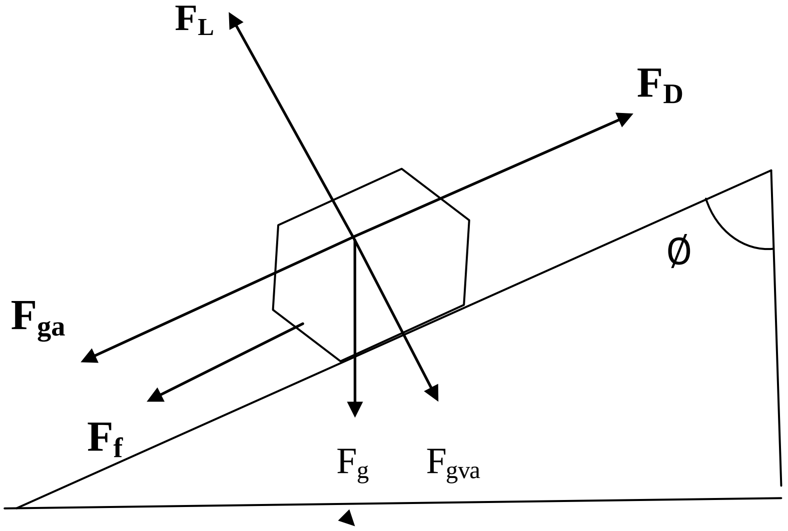


Figure (5.3): Forces acting on the cuttings in inclined wellbore

6. RUBIANDINI'S MODEL

In this chapter, Rubiandini's model is introduced. The model was based on Moore's[6] model for vertical wellbore, Larsen et al. empirical model and Peden et al. experimental data.

Rubiandini claimed that hole-cleaning problems could be mastered by defining the minimum mud rate that had a capability to clean the drilling wellbore. He expressed the minimum mud rate as a sum of the slip velocity and velocity of the fallen cuttings, similar to Larsen. The cuttings velocity was dependent on the wellbore geometry and magnitude of ROP.

Rubiandini believed that mud weight, inclination angle, and RPM were major factors affecting cuttings transport mechanisms. Therefore, corrections factor of these parameters played a main role in the model he proposed.

Rubiandini introduced slip velocity and correction factor for mud weight and angle of inclination. This was done by regression analysis using Larsen's correction factors and experimental data from both Larsen's and Peden's studies. In his research, Rubiandini modified the Moore's slip velocity that was applicable for vertical wellbore in such way so that it would be possible to use in the inclined-until-horizontal wells. Moreover, he introduced a correction factor for RPM based on Peden's work[1] (since RPM values were negligible for several parameters during Larsen's experiments[2]). Finally, Rubiandini presented a new equation for determination of the mud minimum rate that was necessary to lift the cuttings in the inclined-until-horizontal wellbore. He validated his new equation with previously published Larsen's and Peden's experimental data and concluded the following:

- With inclination angle larger than 45˚ degrees, the mud minimum rate of Larsen's model, Larsen's experimental data, and Peden's experiment data had no significant difference with the newly established Rubiandini's model.
- For an inclination angle less than 45˚ degrees, the new model of Rubiandini over-predicted mud minimum rate compared to the methods above.

6.1Rubiandini cuttings lifting equation

The angle correction factor was obtained by using Cartesian dimensionless plotting between slip velocity (V_{slip}) and inclination, based on Larsen's and Peden's data, and was expressed as:

$\theta \leq 45^0$

$$\boldsymbol{C_i = \left[1 + \frac{2\theta}{45}\right]} \quad \text{.......................................} (6.1.1)$$

$\theta \geq 45^0$

$$\boldsymbol{C_i = 2} \quad \text{.......................................} (6.1.2)$$

Based on the dimensionless plotting between slip velocity and inclination, for varied mud density, the following density factor was found:

$$\boldsymbol{C_{mw}} = \frac{\boldsymbol{3+\rho_m}}{\boldsymbol{15}} \quad \text{...}(6.1.3)$$

The RPM correction factor was determined from dimensionless plotting between slip velocity (V_s) and inclination, based on Peden's method, for varied RPM by linear regression and was defined as:

$$\boldsymbol{C_{RPM}} = \frac{\boldsymbol{600-RPM}}{\boldsymbol{600}} \quad \text{...}(6.1.4)$$

Minimum velocity for vertical or horizontal well was written as:

$$\boldsymbol{V_{min} = V_{cut} + [1 + C_i * C_{mw} * C_{RPM}] * V_{slip}} \quad \text{...}(6.1.5)$$

In the equation (6.1.5), a cuttings velocity equation (V_{cut}) was found using the same as in the Larsen's model.

Finally, Rubiandini's minimum velocity for a well inclination below 45°degrees was defined as:

For $\theta \leq 45^0$:

$$\boldsymbol{V_{min} = V_{crit} = V_{cut} + V_{slip}\left[1 + \frac{\theta*(600-RPM)*(3+\rho_m)}{202500}\right]} \quad \text{...}(6.1.6)$$

Rubiandini's minimum velocity for a well inclination above 45°degrees was defined as:

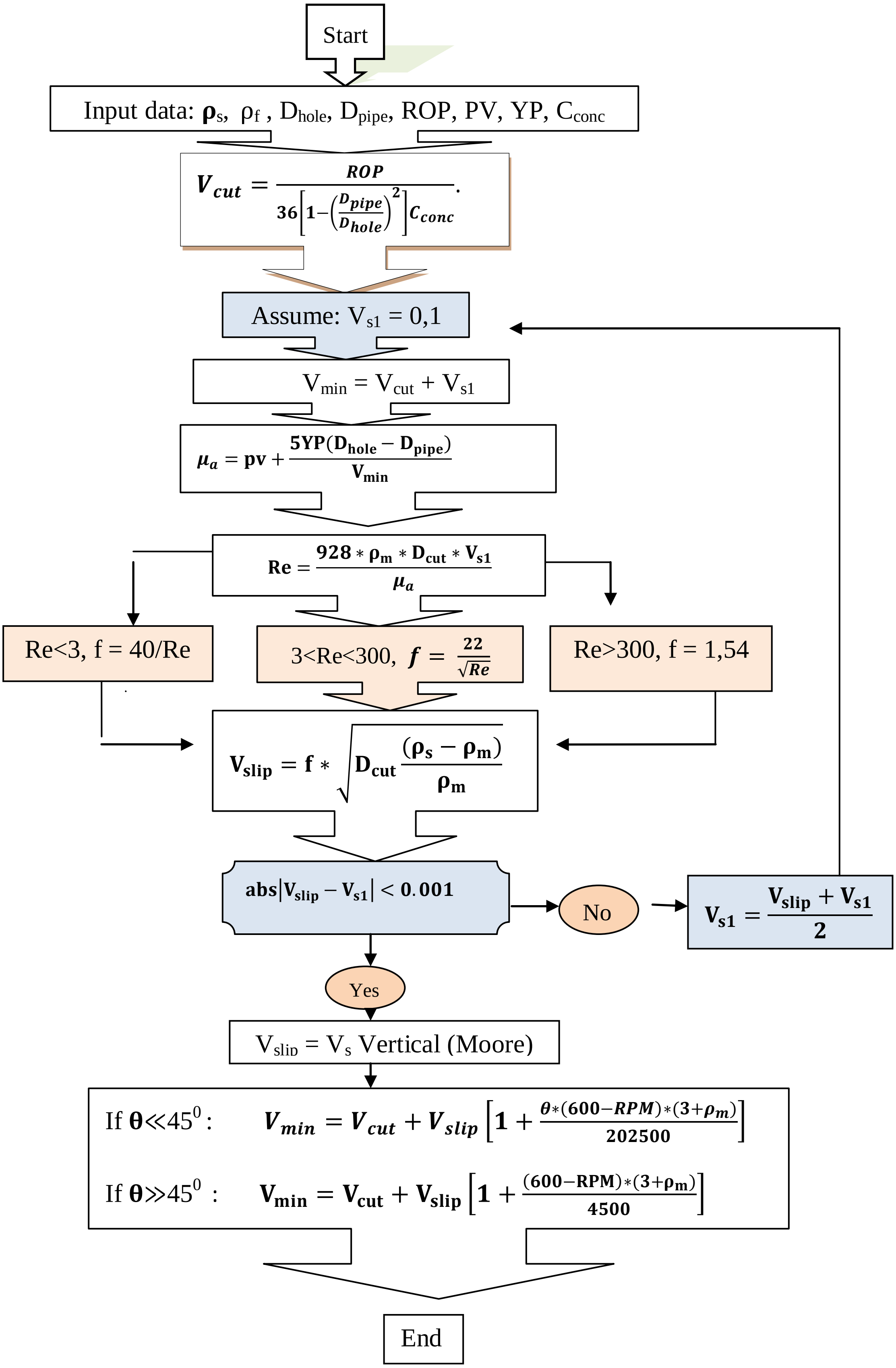
For $\theta \geq 45^0$:

$$\boldsymbol{V_{min} = V_{crit} = V_{cut} + V_{slip}\left[1 + \frac{(600-RPM)*(3+\rho_m)}{4500}\right]} \quad \text{...}(6.1.7)$$

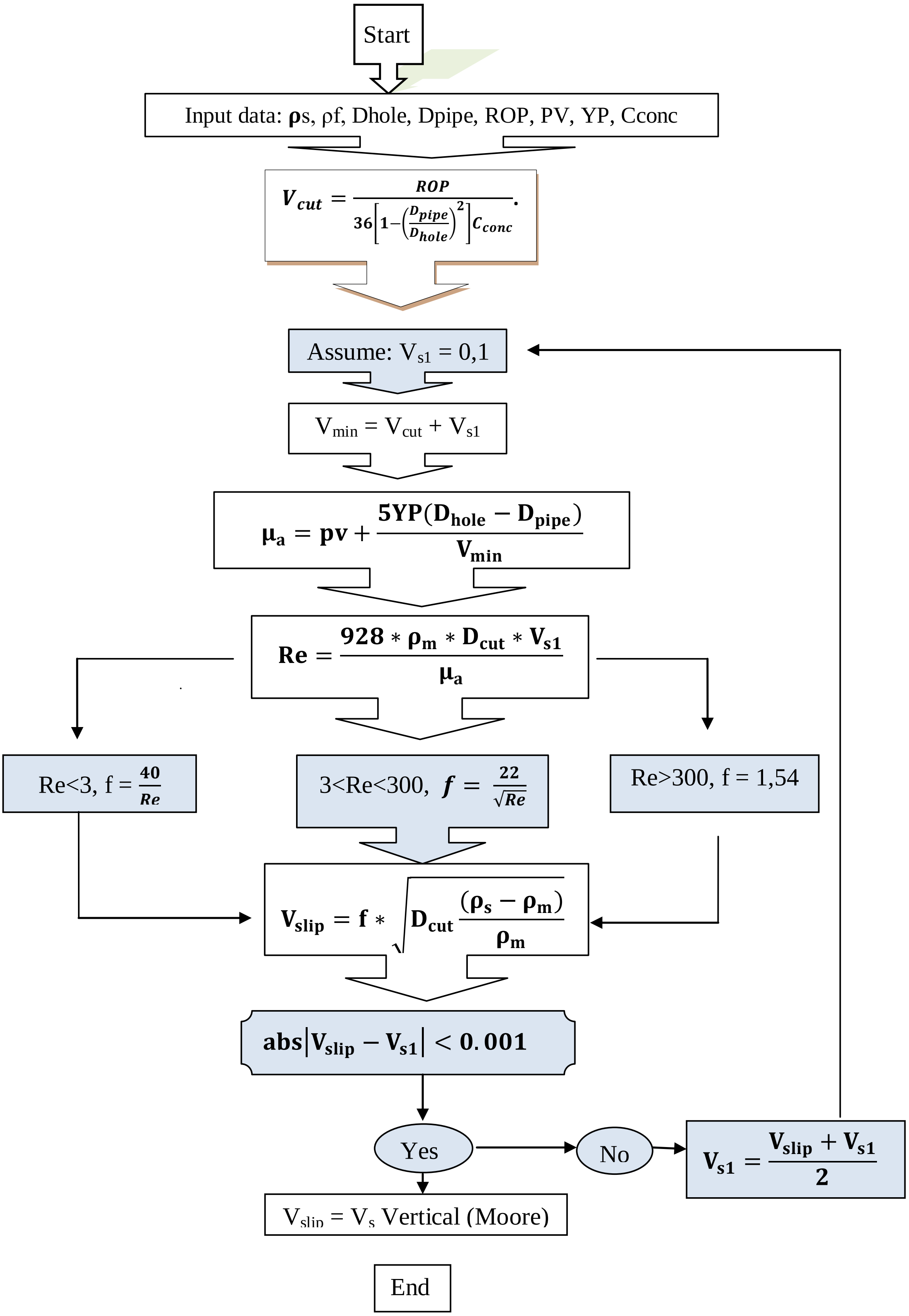
Rubiandini's model is applied for inclination angle between 0˚ and 90˚ degrees. At 0° degrees, Rubiandini's model corresponds to Moore's model for vertical wellbore. Minimum flow velocity defined by Rubiandini showed gradual increase at the inclination interval between 0° and 45° degrees. However, in the inclination angle interval between 45° and 90° degrees, Rubiandini's minimum flow velocity is a constant value. Minimum flow velocity based on Larsen et al. calculations and Peden's experiment have smaller value compared to Rubiandini's minimum flow velocity for inclination less than 45° degrees.

Note that Moore's model in schematic form represented in section 6.3 is taken from Rubiandini's paper[5].

6.2 Rudi Rubiandini's model in schematic form[5]:



6.3 Moore's model in schematic form[5]:



Nomenclature for chapter 6

- C_i = Corection factor for angle, (dimensioless)
- C_{conc} = Cuttings concentration, (%)
- C_{mw} = Correction factor for mud density, (dimensionless)
- C_{RPM} = Correction factor for rpm, (dimensionless)
- C_{size} = Correction factor for cuttings size (dimensionless)
- D_{hole} = Hole diameter, (inch), (m)
- D_{pipe} = Pipe diameter, (inch), (m)
- f = Friction factor, (dimensionless)
- PV = Plastic viscosity (cP), (Pa*s)
- Re = Reynolds number, (dimensionless)
- ROP = Rate of penetration, (ft/hrs), (m/hrs)
- RPM = Drill-pipe rotation par min
- V_{cut} = Cuttings velocity, (ft/s), (m/s)
- V_{crit} = V_{crit} = Critical velocity, (ft/sec), (m/sec)
- V_{min} = Minimum velocity, (ft/s), (ft/s)
- V_{slip} = Slip velocity, (ft/s), (m/s)
- YP = Yield point ($lb_f/100\ ft^2$), (Pa)
- θ = Angleof inclination of wellbore from vertical (degrees)
- ρ_m = Density of mud, (lb_m/gal), (kg/m^3)
- ρ_f = Density of fluid, (lb_m/gal), (kg/m^3)
- ρ_s = Density of cuttings, (lb_m/gal), (kg/m^3)
- μ_a = Apparent viscosity (cP), (Pa*s)

7. MECHANISTIC TWO-LAYER MODEL

The purpose of this chapter is to present a quite different modeling approach, namely the mechanistic. This chapter gives a brief introduction to Kamp's 2-D mechanistic model. More detailed description of the model is given by Kamp and Rivero[4].

Kamp and *Rivero* [4] presented a mechanistic model for calculations of cuttings bed heights and cuttings transport velocities at different rates of penetration in the horizontal wellbore. Kamp and Rivero developed a two-layer model for hole cleaning predictions (further referred to as Kamp's model). In order to solve this mechanistic model they used a numerical solution. First, Kamp and Rivero wrote the conservation equations in dimensionless form and thus, converted these equations into matrix form, which is necessary to solve this system of ordinary differential equations numerically. It was not obvious from the paper how this was done. The results were compared with the results of the Larsen's correlation model. The numerical predictions for bed build-up showed good agreement with Larsen's results. However, predictions for mudflow rate, based on Kamp's model, were ten times lower that Larsen's predictions. Although, it was well known that Larsen's model tended to over-predict mudflow rates observed in the field, Kamp and Rivero identified two main reasons for disagreements in mudflow rate predictions. First, it was not considered that cuttings concentration profile in the heterogeneous layer would be flat and secondly, re-suspended mass flux of the cuttings should be zero at low friction velocities, and be positive only after the friction velocity exceeds a certain critical value. Kamp and Rivero indicated that this model was not a final solution for hole cleaning predictions but it could be used as a supporting tool for mechanical modeling of cuttings transport.

In the next chapter, the central equations that were used by Kamp and Rivero in their mechanistic 2-D model, namely mass conservation equations, momentum equations, mass flux equations, equations for density of heterogeneous and bed-layer and wetted parameters, are presented and briefly described.

Later in chapter 7.3, the way to transform these equations into matrix form is presented. Since this was not shown in details directly in the Kamp and Rivero publication, it was necessary to present Gavignet and Sobey[3] model in order to explain some definitions and to show the transformation of the model into matrix form, which is required for the numerical solution.

The nomenclature is provided at the end of chapter 7.

7. 1 Kamp's two-layer model transport equations

Kamp and Rivero indicated that solving cuttings transport problem in the three-dimensional form was time consuming and demanding job in the field side. Therefore, there was a need for a simpler model for cuttings transport calculation in the field side. According to Kamp and Rivero, the ideal modeling solution would be to combine information from various simple models, for instance one-dimension layer modeling along the wellbore, two-dimensional modeling in different cross sections, and use of separate models for calculating time needed for bed build-up. To solve the two-dimensional model in different cross sections, it was necessary to know velocity profile in the cross section area in each layer. When the velocity variation in the space was known, it was possible to calculate shear stress and forces on the particles. With known shear stress, it was reasonable to calculate the suspension rate of particles.

Figure (7.1) demonstrates the geometry of two-layer model in a horizontal pipe:

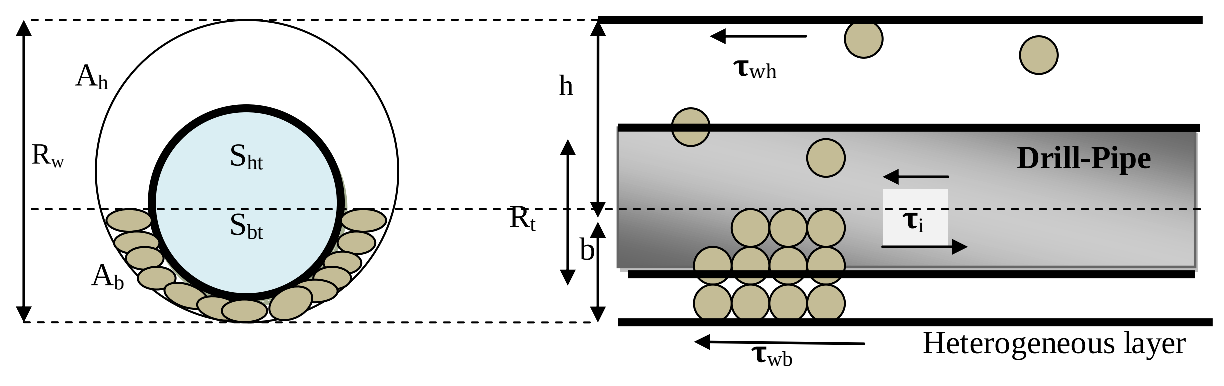


Figure (7.1): A cuttings bed on the bottom of wellbore and a heterogeneous layer on the top.

As shown in figure (7.1), the upper layer is a heterogeneous layer (h), which consists of dispersed cuttings particles in mud. On the bottom of the annulus is accumulation of cuttings that creates a cuttings bed (b). The heterogeneous layer has a cross-section area A_h, and the cuttings bed has a cross-section area A_b.

The cuttings concentration in the heterogeneous layer is described as C_h, while the cuttings bed concentration in the bed layer is defined as C_b. Further, the velocity of the heterogeneous layer is V_h and the velocity of the cuttings bed is V_b. It is assumed that velocity of the heterogeneous layer and the velocity of the cuttings bed have horizontal direction in the Z-axis in the wellbore. The interfacial area between the heterogeneous layer and the cuttings bed is called S_i.

The mass conservation of the cuttings in the heterogeneous layer is defined as:

$$\boldsymbol{\frac{d}{dz}[\rho_S * C_h * V_h * A_h] = -\phi_S * S_i} \quad \text{(7.1.1)}$$

The mass conservation of drilling fluid in the heterogeneous layer is expressed as:

$$\boldsymbol{\frac{d}{dz}[\rho_L * (1 - C_h) * V_h * A_h] = -\phi_L * S_i} \quad \text{(7.1.2)}$$

The mass conservation of drilling fluid and cuttings mixture in the cuttings bed is defined as:

$$\boldsymbol{\frac{d}{dz}[\rho_b * V_b * A_b] = -(\phi_S + \phi_L) * S_i} \quad \text{(7.1.3)}$$

It is assumed that cuttings concentration in the cuttings bed is constant. Then volume ratio of the drilling fluid and cuttings in the bed layer is also constant.

It is also assumed that the heterogeneous layer can be described with one single velocity, and there is no significant slip between the suspended particles and the mud.

This model can easily be expanded by writing separate momentum equations for the dissolved particles and for mud in the heterogeneous layer.

The momentum equation for the heterogeneous layer is defined by:

$$\boldsymbol{\frac{d}{dz}\left[\rho_h * V_h^2 * A_h\right] = -A_h\frac{dp}{dz} - A_h * \rho_h * g * \cos\theta - \tau_{wh} - \tau_i - (\phi_S + \phi_L) * (V_h - V_b)} \;\ldots\ldots \tag{7.1.4}$$

The momentum equation for cuttings bed layer is expressed as:

$$\boldsymbol{\frac{d}{dz}\left[\rho_b * V_b^2 * A_b\right] = -A_b\frac{dp}{dz} - A_b * \rho_b * g * \cos\theta - \tau_{wb} + \tau_i + (\phi_S + \phi_L)(V_h - V_b)} \;\ldots\ldots \tag{7.1.5}$$

In the momentum equations (7.1.4) and (7.1.5), the last term on the right-hand-side of the equation is momentum exchange through particle deposition and re-suspension. Usually, the heterogeneous layer moves faster than the cuttings bed at the bottom of wellbore. Therefore, this can be expressed as $V_b < V_h$. In this case, the interfacial shear stress accelerates the cuttings bed and it leads to reduction of the heterogeneous layer velocity. This means that the particle deposition adds momentum to the cuttings bed and therefore, removes momentum from the heterogeneous layer.

Earlier observations indicated that turbulent flow in the heterogeneous layer played the main role in keeping cuttings in suspension. It has been noticed that in order to achieve a sufficient cuttings transport in a horizontal wellbore, drilling fluid with low viscosity and high velocity gave the best results. A turbulent flow kept the cuttings in the suspension, but it was not clear which of parameters would transport cuttings. Still, the nature of the cuttings in the suspension is not very well understood. The turbulent suspension is a balance between particle settling due to gravity and a turbulent diffusion of particles, caused by large scale eddies.

The mass flux of cuttings that are deposited per unit interface is described as $\boldsymbol{\phi}_{\text{s,dep.}}$, and mass flux of the cuttings that are re-suspended per unit interval is $\boldsymbol{\phi}_{\text{s,susp.}}$

Then the total mass flux of cuttings in the equations (7.1.1), (7.1.3), (7.1.4), and (7.1.5) is defined as follows:

$$\boldsymbol{\phi_S = \phi_{s,dep} - \phi_{s,susp}} \;\ldots\ldots \tag{7.1.6}$$

The mass flux of cuttings that is deposited per unit interface is introduced as "$\boldsymbol{\phi}_{\text{s,dep}}$" and equation for flux deposition is defined as:

$$\phi_{s,dep} = C_h * \rho_s * V_{s,y} \quad \text{..........} (7.1.7)$$

Mass flux of the cuttings that are re-suspended per unit interval is introduced as "$\phi_{s,susp}$", and equation for re-suspension flux is defined as:

$$\phi_{s,susp} = C_b * \rho_s * V_{\tau i} * H(h) \quad \text{..........} (7.1.8)$$

By using equations (7.1.7) and (7.1.8), the total mass flux of particles is defined as :

$$\phi_S = \phi_{s,dep} - \phi_{s,susp} = \rho_s\{C_h * V_s - C_b * U_{\tau i} * H(h)\} \quad \text{..........} (7.1.9)$$

The mass flux of liquid that is deposited per unit interface is describe as "$\phi_{L,dep}$", and mass flux of the liquid that are re-suspended per unit interval describes as "$\phi_{L,susp}$".

Then the total mass flux of liquid in the equations (7.1.3) and (7.1.4) is defined as:

$$\phi_L = \phi_{L,dep} - \phi_{L,susp} \quad \text{..........} (7.1.10)$$

It is known that drilling fluid densities can be changed due to variations in pressure and temperature. However, for simplicity, it is assumed that both cuttings and drilling mud has constant density.

The equation for heterogeneous layer density, used in the momentum equation (7.1.4) for heterogeneous layer, is defined as:

$$\rho_h = C_h * \rho_s - (1 - C_h) * \rho_L \quad \text{..........} (7.1.11)$$

The equation for heterogeneous layer density is not constant, since the cuttings concentration in the heterogeneous layer is varying.
The equation for cuttings bed density, used in equations (7.1.3) and (7.1.5), can be described as follows:

$$\rho_b = C_b * \rho_S + (1 - C_b) * \rho_L \quad \text{..........} (7.1.12)$$

The equation for bed density (7.1.12) is constant, since it is assumed that all parameters in this equation are constant.
"Wetted perimeters" of the wellbore are defined as S_{bW} for cuttings bed interval and S_{hW} for heterogeneous interval. For drill pipe, "wetted perimeters" are presented as S_{bt} for cuttings bed and S_{ht} for heterogeneous layer. The "wetted perimeters" are shown in figure (7.1).

Wetted perimeters in the heterogeneous interval:

$$S_h = S_{ht} + S_{hw} \quad \text{..........} (7.1.13)$$

Wetted perimeters in the cuttings bed interval:

$$S_b = S_{bt} + S_{bw} \quad \text{..........} (7.1.14)$$

Next chapter (7.2) provides deeper understanding of the mechanistic 2-layer model developed by Gavignet and Sobey[3]. Several parameters, such as “wetted perimeter” and cuttings bed height that have been used in this chapter, are explained in details in the following chapter.

7. 2 GAVIGNET’S mechanistic two - layer model

In 1989, *Gavigant* and *Sobey*[3] published a paper where they presented a two-layer model for cuttings transport in an eccentric annulus with a Non-Newtonian drilling fluid (further referred as Gavignet’s model). In their study, *Gavigant* and *Sobey* assumed that cuttings were falling towards the lower side of the wellbore due to inclination of the well and gravity and thus formed a cuttings bed.

As it was explained in the previous section, the heterogeneous layer has a cross-section area, A_h, the cuttings bed has a cross-section area, A_b (figure 7.2.1), and perimeter that are in contact with both the heterogeneous and cuttings layers, S_h and S_b, respectively. The interface between S_h and S_b is called S_i.

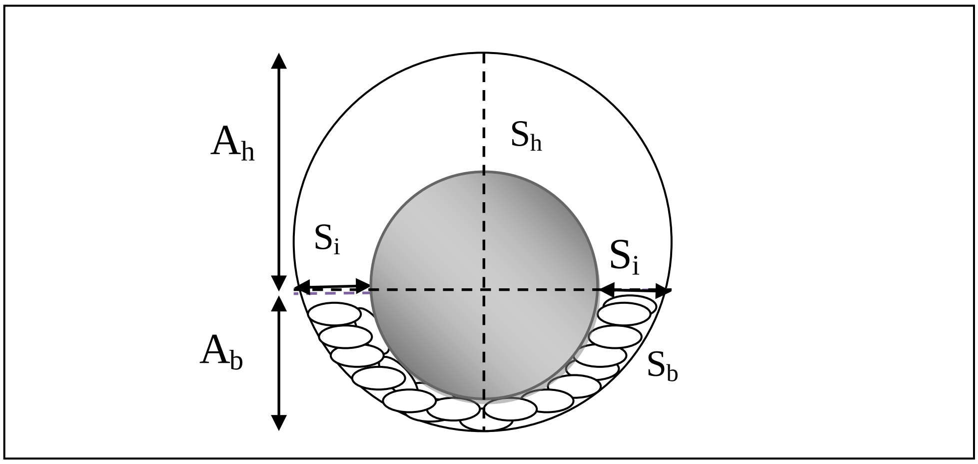


Figure (7.2.1): In eccentric annulus, heterogeneous layer is lying in the upper part of annulus and cuttings bed on the bottom. (Modified from Gavignet and Sobey[3])

During the study, the hydrostatic pressure was neglected since the cuttings bed was closely packed so that cuttings supported each other. Therefore, it was assumed equal hydraulic pressure in both the heterogeneous and the bed layer.

The momentum balance for heterogeneous layer is equal to:

$$\boldsymbol{A_h\left(\frac{\partial p}{\partial z}\right) = -\tau_h * S_h - \tau_i * S_i} \quad \text{..........(7.2.1)}$$

Moreover, the momentum balance for cuttings bed layer is equal to:

$$\boldsymbol{A_b\left(\frac{\partial p}{\partial z}\right) = -\tau_b * S_b - \tau_i * S_i} \quad \text{..........(7.2.2)}$$

If it is assumed that pressure gradient (∂p/∂z) in the equations (7.2.1) and (7.2.2) are equal then it is possible to combine these two equations to derive an equation, which involves stress at the annulus walls and interfacial stress:

$$\boldsymbol{A_b * \tau_h * S_h + A * \tau_i * S_i = A_h * \tau_b * S_b} \quad \text{.......(7.2.3)}$$

To solve equation (7.2.3), the equations for shear stresses in the heterogeneous layer and in the bed layer should be described as a function of heterogeneous layer velocity and cuttings bed velocity.

The wall shear stress in heterogeneous layer is presented as follows:

$$\boldsymbol{\tau_h = \frac{1}{2} * f(Re, h) * \rho_h * V_h^2} \quad \text{.......(7.2.4)}$$

The cuttings bed consists of a large fraction of mud and smaller fraction of cuttings particles. The wall shear stress in the cuttings bed layer consists of mud and cuttings fraction.

Equation for wall shear stress in cuttings bed layer is defined as:

$$\boldsymbol{\tau_b = \frac{1}{2} * f(Re, b) * \rho_h * V_b^2 + k_f(\rho_b - \rho_h) * g * C * \sin\theta * (\frac{A_b}{S_b})} \quad \text{.......(7.2.5)}$$

The interfacial shear stress between heterogeneous and cuttings bed layers is represented as follows:

$$\boldsymbol{\tau_i = \frac{1}{2} * f_i * \rho_h(V_h - V_b) * |V_h - V_b|} \quad \text{.......(7.2.6)}$$

In equations (7.2.4), (7.2.5), and (7.2.6), friction factor and Reynolds number are unknown. In general, the distribution of velocities in a two-layer model in annulus is very complex and we have to simplify it for further calculations. Based on previously published assumptions for calculation Reynolds number in the heterogeneous layer (Re_h), it is assumed that the annulus space is totally filled with drilling fluid. To calculate Reynolds number in the cuttings bed (Re_b), the liquid friction that occurs between drilling fluid and cuttings bed is disregarded. (For more details on the assumptions, view Gavignet and Sobey[1].)

In order to solve the model it is necessary to express different cross-section areal and wetted perimeters in terms of bed height.

The equation for total annulus area in the wellbore is defined as follows:

$$\boldsymbol{A = \pi(r_o^2 - r_i^2)} \quad \text{.......(7.2.7)}$$

In the figure below, it is assumed that wellbore radius is defined as “r_0”, distance from the center of the wellbore to the top of the cuttings bed is expressed as “l”, angle of the bed height is “**β**”, and bed thickness is “h”.

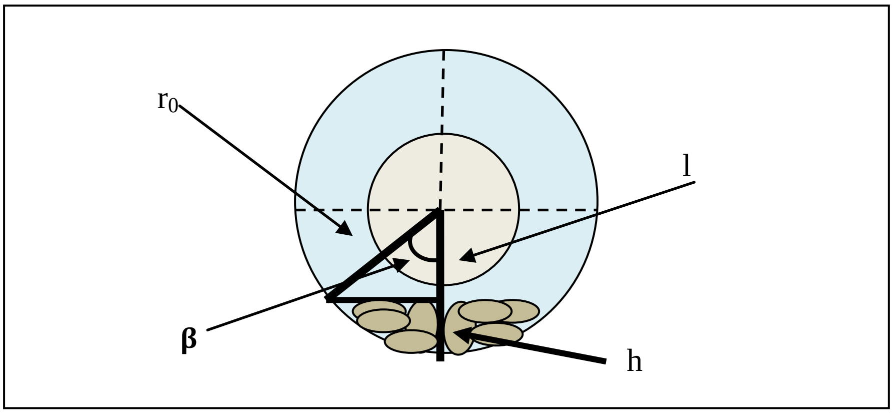


Figure 7.2.2: Relation between cuttings bed height and **β.**

By geometry, “cos **β**” is defined as:

$$\cos \boldsymbol{\beta} = \frac{l}{r_0} \qquad (7.2.8)$$

Then, equation for cuttings bed height can be expressed as:

$$h = r_0 - \ l = \ r_o(1 - \cos \boldsymbol{\beta}) \qquad (7.2.9)$$

According to Gavignet and Sobey[3], three cases must be considered in order to determine geometrical parameters (figure (7.2.3)):

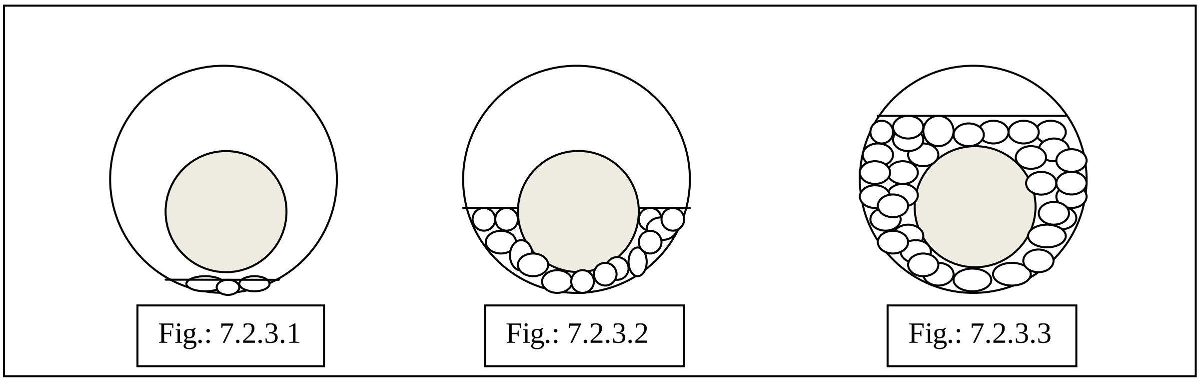


Fig.: 7.2.3.1

Fig.: 7.2.3.2

Fig.: 7.2.3.3

Figure (7.2.3): Three possible configurations for drill pipe location relative to cuttings bed height.

In each of these cases, the cross-section area of cuttings bed layer (A_b), cross-section area of heterogeneous layer (A_h) and “wetted perimeters” are varying.

The equation for total “wetted perimeter” is expressed as follows:

$$\boldsymbol{S = 2\pi(r_i + r_o)} \qquad (7.2.10)$$

Case1:

As illustrated in the figure (7.2.3.1), the drill-pipe is located above the cuttings bed, and there is no connection between the drill-pipe and cuttings bed. In this situation, drill-pipe geometry can be described as follows:

$$\boldsymbol{r_o} \cos \boldsymbol{\beta} > (e - \boldsymbol{r_i}) \quad \text{(7.2.11)}$$

Equation for cross-section area of the bed layer (A_b), in the figure (7.2.3.1) can be defined as:

$$\boldsymbol{A_b} = \boldsymbol{r_o}^2(\boldsymbol{\beta} - \sin \boldsymbol{\beta} * \cos \boldsymbol{\beta}) \quad \text{(7.2.12)}$$

With use of equations (7.2.7) and (2.2.12), the cross-section area in the heterogeneous layer (A_h) can be calculated:

$$\boldsymbol{A_h} = \boldsymbol{A} - \boldsymbol{A_b} \quad \text{(7.2.13)}$$

Equation for "wetted perimeter" of bed layer, in contact with wall (S_b), can be defined as follows:

$$\boldsymbol{S_b} = 2\boldsymbol{r_o}\boldsymbol{\beta} \quad \text{(7.2.14)}$$

With use of equations (7.2.10) and (7.2.14), the perimeter in the heterogeneous layer (S_h) is defined as:

$$\boldsymbol{S_h} = \boldsymbol{S} - \boldsymbol{S_b} \quad \text{(7.2.15)}$$

Equation for interface perimeter (S_i) between cuttings bed and heterogeneous layer can be expressed as follows:

$$\boldsymbol{S_i} = 2\boldsymbol{r_o} \sin(\boldsymbol{\beta}) \quad \text{(7.2.16)}$$

Case 2:

As it is illustrated in the figure (7.2.3.2), the drill-pipe is partially buried in the cuttings bed, and drill pipe geometry can be defined as:

$$\boldsymbol{r_o} \cos \boldsymbol{\beta} > (\boldsymbol{e} - \boldsymbol{r_i}) \quad \boldsymbol{and} \quad \boldsymbol{r_o} \cos \boldsymbol{\beta} < (e - \boldsymbol{r_i}) \quad \text{(7.2.17)}$$

If it is assumed that cuttings bed creates an angle "α" with the drill pipe, then this angle can be represented as follows:

$$\boldsymbol{\alpha} = \cos^{-1}[(\boldsymbol{r_o} \cos \boldsymbol{\beta} - \boldsymbol{e})/\boldsymbol{r_i}] \quad \text{(7.2.18)}$$

The equation for cross-section area of bed layer (A_b) is defined as follow:

$$\boldsymbol{A_b} = \boldsymbol{r_o}^2(\boldsymbol{\beta} - \boldsymbol{sin\beta} * \boldsymbol{cos\beta}) - \boldsymbol{r_i^2}(\boldsymbol{\alpha} - \sin \boldsymbol{\alpha} * \cos \boldsymbol{\alpha}) \quad \text{(7.2.19)}$$

By using equations (7.2.7) and (7.2.19), equation for cross-section area in the heterogeneous layer (A_h) can be calculated:

$$\boldsymbol{A_h = A - A_b} \quad (7.2.20)$$

Equation for “wetted perimeter” of the bed layer that is in contact with wall (S_b) is expressed as follows:

$$\boldsymbol{S_b = 2(r_o\beta - r_i\alpha)} \quad (7.2.21)$$

Equation for interface perimeter (S_i) between cuttings bed and heterogeneous layer is defined as:

$$\boldsymbol{S_i = 2r_o \sin(\beta) - 2r_i \sin(\alpha)} \quad (7.2.22)$$

By combining equations (7.2.10) and (7.2.22), equation for “wetted perimeter” of heterogeneous layer (S_h) is defined as follows:

$$\boldsymbol{S_h = S - S_i} \quad (7.2.23)$$

Case 3:

As shown in the figure (7.2.3.3), drill pipe is completely buried under the cuttings bed. The geometry for this case can be described as follows:

$$\boldsymbol{r_o cos\beta} < (e - ri) \quad (7.2.24)$$

Equation for cross-section area in the heterogeneous layer (A_h) is calculated as following:

$$\boldsymbol{A_h = A(\pi - \beta) - \sin(\pi - \beta)\cos(\pi - \beta) * r_o^2} \quad (7.2.25)$$

By using equations (7.2.7) and (7.2.25), equation for cross-section area of bed layer (A_b) can be defined as:

$$\boldsymbol{A_b = A - A_h} \quad (7.2.26)$$

Equation for “wetted perimeter”of heterogeneous layer in contact with wall (S_h) is calculated as follows:

$$\boldsymbol{S_h = 2r_o * \sin(\pi - \beta)} \quad (7.2.27)$$

By combining equations (7.2.10) and (7.2.25), equation for “wetted perimeter” of bed layer in contact with wall (S_b) is expressed as:

$$\boldsymbol{S_b = S - S_h} \quad (7.2.28)$$

- S= Total wetted perimeter
- S_h = Perimeter of heterogeneous layer

Equation for interface perimeter (S_i) between cuttings bed and heterogeneous layer is calculated as:

$$\boldsymbol{S_i = 2r_o \sin(\pi - \beta)} \quad \text{..........(7.2.29)}$$

It is assumed that flow regime in the heterogeneous layer is turbulent, and stresses in the bed layer occur due to cuttings sliding against the wellbore wall.

Gavignet and Sobey concluded that cuttings bed did not arise when the wellbore was vertical. In this case, the flow velocity was either high enough to transport cuttings up to surface against the gravity force or cuttings would fall down in the lower part of the wellbore. Furthermore, in a horizontal well, when there were no forces to push cuttings forward, the cuttings bed would grow until the flow velocity was high enough to prevent any cuttings bed from building up.

According to Gavignet and Sobey, drill-pipe eccentricity had a large influence on the cuttings bed height. When the cuttings bed increased and met the drill-pipe, this would result in decreasing of the interfacial area between cuttings bed and the heterogeneous mud layer. By increasing well deviation, the drill-pipe eccentricity would increase. Gavignet and Sobey indicated that drill-pipe eccentricity was important only when the cuttings beds were in contact with the drill-pipe. The dynamics of the cuttings bed was highly dependent on friction forces at the wall and in the interfacial layer between cuttings bed and drilling fluid layer (heterogeneous layer).

Gavignet and Sobey stated that drill pipe size had an important effect on the cuttings transport. They advised to drill highly deviated wellbore with as large drill-pipe as possible.

They also concluded that cuttings size was another important parameter that influenced cuttings transport, since interfacial stress was strongly dependent of cuttings size on the bed. In general, the drag force on the smaller cuttings is lower and it needs a higher flow rate to transport smaller cuttings.

In the next chapter, the steps needed in advance in order to solve the Kamp's model numerically are described since it was not expressed in details in Kamp's paper. Here, the definitions given by Gavignet and Sobey are required.

7. 3 Proposed numerical solution for two-layer mechanistic model

In order to solve Kamp's two-layer model numerically, the authors expressed the conservation laws in matrix form. This leads to matrix multiplication, shown as below:

$$\begin{bmatrix} \boldsymbol{a_{11}} & \boldsymbol{a_{12}} & \boldsymbol{a_{13}} & \boldsymbol{a_{14}} & \boldsymbol{a_{15}} \\ \boldsymbol{a_{21}} & \boldsymbol{a_{22}} & \boldsymbol{a_{23}} & \boldsymbol{a_{24}} & \boldsymbol{a_{25}} \\ \boldsymbol{a_{31}} & \boldsymbol{a_{32}} & \boldsymbol{a_{33}} & \boldsymbol{a_{34}} & \boldsymbol{a_{35}} \\ \boldsymbol{a_{41}} & \boldsymbol{a_{42}} & \boldsymbol{a_{43}} & \boldsymbol{a_{44}} & \boldsymbol{a_{45}} \\ \boldsymbol{a_{51}} & \boldsymbol{a_{52}} & \boldsymbol{a_{53}} & \boldsymbol{a_{54}} & \boldsymbol{a_{55}} \end{bmatrix} * \begin{bmatrix} \frac{\boldsymbol{dC_h}}{\boldsymbol{dz'}} \\ \frac{\boldsymbol{dU'_h}}{\boldsymbol{dz'}} \\ \frac{\boldsymbol{dU'_b}}{\boldsymbol{dz'}} \\ \frac{\boldsymbol{dp'}}{\boldsymbol{dz'}} \\ \frac{\boldsymbol{dh'}}{\boldsymbol{dz'}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{b_1} \\ \boldsymbol{b_2} \\ \boldsymbol{b_3} \\ \boldsymbol{b_4} \\ \boldsymbol{b_5} \end{bmatrix} \quad \text{..........(7.3.1)}$$

The purpose of matrix multiplication is to simplify the notation and solve the system of ordinary differential equations. If we write:

$$\boldsymbol{A = [a_{ij}]\ and\ X' = \begin{bmatrix} X'_1 \\ \vdots \\ X'_n \end{bmatrix} and\ b = \begin{bmatrix} b_1 \\ \vdots \\ b_n \end{bmatrix}}$$

Then [A], [X'] and [b] are the coefficient matrix, the unknown vector, and the constant vector for a linear system, respectively. The matrix product (AX') is defined in such way that the entire system of ordinary differential equation (7.3.1) is reduced to the single matrix equation:

$$\boldsymbol{AX' = b} \quad \text{.......(7.3.2)}$$

The solution for the unknown parameter [X'] is calculated as follows:

$$\boldsymbol{X' = \frac{dx}{dz'} = [C_h, V'_h, V'_b, P', h']^T = A^{-1}b} \quad \text{.......(7.3.3)}$$

The authors introduced dimensionless variables when they transformed the equation system into matrix form. Here, the main steps are presented in how the transformation was performed.

The mass conservation of the cuttings in the heterogeneous layer is defined as:

$$\boldsymbol{\frac{d}{dz}[\rho_S * C_h * V_h * A_h] = -\phi_S * S_i}.$$

The coordinates along the wellbore direction "z" in equation (7.1.1) are expressed in dimensionless form:

$$\boldsymbol{z' = \frac{z}{r_0}} \quad \text{.......(7.3.4)}$$

Then "d/dz" in equation (7.1.1) is expressed by using equation (7.3.4):

$$\boldsymbol{\frac{d}{dz} = \frac{1}{r_0} * \frac{d}{dz'}} \quad \text{.......(7.3.5)}$$

Velocity of the heterogeneous layer "V_h" written in dimensionless form is defined:

$$\boldsymbol{V'_h = \frac{V_h}{V_{mix}}} \quad \text{.......(7.3.6)}$$

where $\boldsymbol{V_{mix} = V_h + V_b}$.

By combining equations (7.3.5) and (7.3.6), the equation (7.1.1) can be re-written as:

$$\boldsymbol{\frac{1}{r_0} * \frac{d}{dz'}[\rho_s * C_h * V_{mix} * V'_h * A_h] = -\emptyset_s * S_i} \quad \text{.......(7.3.7)}$$

The right hand side in the equation (7.3.7) is constant. Then the constant parameters from the left side are moved to the right side of the equation (7.3.7).

So, the equation (7.3.7) can be expressed as follows:

$$\frac{d}{dz'}\left[\boldsymbol{C_h} * \boldsymbol{V_h'} * \boldsymbol{A_h}\right] = -\frac{\emptyset_s * S_i * r_0}{\rho_s * V_{mix}} \quad \text{.........}(7.3.8)$$

The partial derivation of the left side of the equation (7.3.8) can be described as follows:

$$\boldsymbol{V_h'} * \boldsymbol{A_h} * \frac{d}{dz'}\boldsymbol{C_h} + \boldsymbol{C_h} * \boldsymbol{A_h} * \frac{d}{dz'}\boldsymbol{V_h'} + \boldsymbol{C_h} * \boldsymbol{V_h'} * \frac{d}{dz'}\boldsymbol{A_h} = -\frac{\emptyset_s * S_i * r_0}{\rho_s * V_{mix}} \quad \text{.........}(7.3.9)$$

The procedure of matrix multiplication was applied to all five equations (7.1.1), (7.1.2), (7.1.3), (7.1.4), and (7.1.5). After some mathematical operations, the final equation is written in matrix form as:

$$\boldsymbol{a_{11}} * \frac{d}{dz'}\boldsymbol{C_h} + \boldsymbol{a_{12}} * \frac{d}{dz'}\boldsymbol{V_h'} + \boldsymbol{a_{13}} * \frac{d}{dz'}\boldsymbol{V_b'} + \boldsymbol{a_{14}}\frac{d}{dz'}\boldsymbol{p'} + \boldsymbol{a_{15}}\frac{d}{dz'}\boldsymbol{h'} = \boldsymbol{b_1} \text{.........}(7.3.10),$$

where $\boldsymbol{a_{11}} = \boldsymbol{V_h'} * \boldsymbol{A_h}$, $\boldsymbol{a_{12}} = \boldsymbol{C_h} * \boldsymbol{A_h}$, $\boldsymbol{a_{13}} = \boldsymbol{a_{14}} = \boldsymbol{0}$, $\boldsymbol{a_{15}} = \boldsymbol{C_h} * \boldsymbol{V_h'}$, and $\boldsymbol{b_1} = -\frac{\emptyset_s * S_i * r_0}{\rho_s * V_{mix}}$

By comparing the equations (7.3.9) and (7.3.10), it is notable that $(\frac{d}{dz'}\boldsymbol{A_h})$ is replaced by $(\frac{d}{dz'}\boldsymbol{h'})$. Since $(\boldsymbol{A_h})$ is not a dimensionless variable, it is necessary to express it in dimensionless form. The following mathematical expressions provide the explanation.

By referring to Gavignet’s model and equation for cuttings bed height (7.2.9), equation for cuttings bed height in dimensionless form can be written as:

$$\boldsymbol{h'} = \frac{\boldsymbol{h}}{\boldsymbol{r_0}} = [\boldsymbol{1} - \boldsymbol{\cos\beta}] \quad \text{.........}(7.3.11)$$

Further, we refer to **<u>case 1</u>**, where drill-pipe is placed above the cuttings bed and there is no connection between the drill-pipe and cuttings bed.

From equation (7.2.13), it is knows that cross-section area in the heterogeneous layer (A_h) is equal to total annulus area (A) minus cross-section area of bed layer (A_b).

From equation (7.3.11), it is easy to define $\boldsymbol{\cos\beta}$:

$$\boldsymbol{\cos\beta} = \boldsymbol{1} - \boldsymbol{h'} \quad \text{.........}(7.3.12)$$

By combining equations (7.3.12) and trigonometry relations, the $\boldsymbol{\sin\beta}$ is defined:

$$\boldsymbol{\sin\beta} = \sqrt{\boldsymbol{1} - (\boldsymbol{1} - \boldsymbol{h'})^2} \quad \text{.........}(7.3.13)$$

Finally, it is possible to calculate angle between cuttings bed and wellbore wall (β):

$$\boldsymbol{\beta} = \boldsymbol{\cos^{-1}}(\boldsymbol{1} - \boldsymbol{h'}) \quad \text{.........}(7.3.14)$$

By using equations (7.2.7), (7.2.12), (7.2.13) and (7.3.12), (7.3.13), and (7.3.14), equation for cross-section area in the heterogeneous layer (A_h) can be defined as:

$$\boldsymbol{A_h = \pi\left(r_0^2 - r_i^2\right) - r_0^2\left[\cos^{-1}(1-h') - \sqrt{1-(1-h')^2} * (1-h')\right]} \text{ ....(7.3.15)}$$

By differentiation equation (7.3.15), we can define ($\boldsymbol{\frac{d}{dz'}A_h}$):

$$\boldsymbol{\frac{d}{dz'}A_h = -r_0^2\frac{d}{dz'}\left[\cos^{-1}(1-h') - \sqrt{1-(1-h')^2} * (1-h')\right]} \text{ ....(7.3.16)}$$

Further, it is assumed that U= ($\boldsymbol{1-h'}$), then equation (7.3.16) can be written as:

$$\boldsymbol{\frac{d}{dz'}A_h = -r_0^2\frac{d}{dz'}\left[\cos^{-1}(U) - \sqrt{1-(U)^2} * (U)\right]} \text{ ....(7.3.17)}$$

Moreover, after derivation, the equation (7.3.17) is expressed as:

$$\boldsymbol{\frac{d}{dz'}A_h = -r_0^2\left[-\frac{1}{\sqrt{U^2}}\frac{du}{dz'} - \left(\frac{1}{2\sqrt{(1-U^2)}} * \frac{-2U*du}{dz'} * (U)\right) + \sqrt{1-U^2} * \frac{du}{dz'}\right]} \text{ ....(7.3.18)}$$

Finally, with input of U= ($\boldsymbol{1-h'}$), equation (7.3.18) is defined as:

$$\boldsymbol{\frac{d}{dz'}A_h = -r_0^2\left[\frac{1}{\sqrt{(1-h')^2}}\frac{dh'}{dz'} - \left(\frac{1}{2\sqrt{(1-(1-h')^2)}} * \frac{2(1-h')*dh'}{dz'} * (1-h')\right) - \sqrt{1-(1-h')^2} * \frac{dh'}{dz'}\right]}$$

....(7.3.19)

Now, having expressed ($\boldsymbol{\frac{d}{dz'}A_h}$) in terms of dimensional bed height, it is possible to re-write the equation (7.3.9) and determine the first row in matrix A and item no.1 in vector b.

The mathematical calculations from (7.3.4) to (7.3.19) must be repeated in order to write equations (7.1.2), (7.1.3), (7.1.4), and (7.1.5) in matrix form. The coefficients in the matrix system will change for case 1, 2 and 3.

For further information on how the matrix system was solved the author refer to Kamp and Rivero[4].

Nomenclature for chapter 7

- A = Total annulus area (ft^2), (m^2)
- A_b = Cross-section area of bed layer (ft^2), (m^2)
- A_h = Cross-section area in the heterogeneous layer (ft^2), (m^2)
- [A] = coefficient matrix
- b = Cuttings bed
- $[b_n]$ = constant vectors
- C = Volumetric cuttings concentration (vol %)
- C_b = Cuttings concentration at bed interface (vol %)
- C_h = Cuttings concentration in the heterogeneous layer (vol %)
- e = Drill-pipe eccentricity (inch), (mm)
- f = Friction factor in pipe (dimensionless)
- f_i = Interfacial friction factor (dimensionless)
- g= Gravitation (32,152 ft/s^2), (m/s^2)
- H = Heterogeneous layer
- H(h) = Heaviside function
- h = Bed height (inch), (m)
- $h^{'}$ = Bed height in dimensionless form (dimensionless)
- k_f = Solids/solids friction coefficient
- L = distance between center of pipe and center of the hole
- P= Pressure (lb_f/in_2), (kPa)
- $P^{'}$ = Pressure in dimensionless form (dimensionless)
- Re,b = Reynolds number for bed layer (dimensionless)
- Re,h = Reynolds number for heterogeneous layer (dimensionless)
- r_i = Drill pipe diameter (inch), (m)
- r_o = Hole diameter (inch), (m)
- R_t = Drill-pip outer diameter (inch), (m)
- R_w = Wellbore radius (inch), (m)
- S= Total wetted perimeter (inch), (m)
- S_b = Wetted perimeter of cuttings layer in contact with wall (inch), (m)
- S_{bt}= Wetted perimeters in the drill-pipe (inch), (m)
- S_{bw}= Wetted perimeters in the wellbore (inch), (m)
- S_h= Wetted perimeter of heterogeneous layer in contact with wall (inch), (m)
- S_{ht}= Wetted perimeters in the drill-pipe (inch), (m)
- S_{hw}= Wetted perimeters in the wellbore (inch), (m)
- S_i = Interface wetted Perimeter (inch), (m)
- V_b = Velocity of the cuttings bed layer (ft/sec), (m/sec)
- V_h = Velocity of heterogeneous layer (ft/sec), (m/sec)
- V_{mix} = Velocity of mixture (Cuttings and drilling fluid (ft/sec), (m/sec)
- $V_{\tau i}$ = Friction velocity (ft/sec), (m/sec)

- V'_b = Velocity of bed layer in dimensionless form (dimensionless)
- V'_h = Velocity of heterogeneous layer in dimensionless form
- V_s= Settling velocity of a particle in a stationary mud (ft/sec), (m/sec)
- $V_{s,y}$ = Cuttings settling velocity in the y- direction (ft/sec), (m/sec)
- [X’] = unknown vectors
- z = Coordinates along the wellbore direction
- z' = Coordinates along the wellbore direction in dimensionless form
- α= Cuttings bed angle with bottom of drill pipe (degrees)
- β = Angle between cuttings bed and wellbore wall (degrees)
- θ= Well inclination angle (degrees)
- $\boldsymbol{\rho_b}$ = Density of bed layer (lb_m/gal), (g/cm3)
- $\boldsymbol{\rho_h}$ = Density of heterogeneous layer (lb_m/gal), (g/cm3)
- $\boldsymbol{\rho_l}$ = Density of drilling fluid (lb_m/gal), (g/cm3)
- $\boldsymbol{\rho_S}$ = Density of solids particles (lb_m/gal), (g/cm3)
- τ_b = Wall shear stress in the bed layer ($lb_f/100\ ft^2$), (Pa)
- τ_i = Interfacial shear stress ($lb_f/100\ ft^2$), (Pa)
- τ_h = Wall shear stress in the heterogeneous layer ($lb_f/100\ ft^2$), (Pa)
- $\tau_{wh\,=}$ Wall shear stress on the heterogeneous layer ($lb_f/100\ ft^2$), (Pa)
- τ_{wb} = Wall shear stress on the cuttings bed ($lb_f/100\ ft^2$), (Pa)
- $\emptyset_L$ = Mass flux of drilling fluid ($kg\cdot m^{-2}\cdot s^{-1}$)
- $\emptyset_{L,dep.}$= Mass flux of liquid that deposit per unit interface
- $\emptyset_{L,susp.}$ = Mass flux of the liquid that are re-suspended per unit interval
- $\emptyset s$ = Mass flux of cuttings
- $\emptyset_{s,dep}$ = Mass flux of cuttings that deposit per unit interface
- $\emptyset_{s,susp.}$ = Mass flux of the cuttings that are re-suspended per unit interval

8. CALCULATONS USING LARSEN'S AND RUBIANDINI'S MODELS

In this chapter, we focus on Larsen's and Rubiandini's models in greater details. By using MatLab computer program, we draw prediction curves based on the data that was used by Larsen in his research. The main purpose of this work is to establish the differences between these two models and to observe how various drilling parameters affect cutting transport. It is vital to mention that during the modeling, all drilling variables are kept constant and only one of them is varying for each curve. In this study, we consider the following parameters:

- Mud weight
- ROP
- Cuttings size
- Mud rheology
- Drill pipe outside diameter
- RPM

Note that Larsen, in his study, focused on mud rheology, ROP, cuttings size, and mud weight, while Rubiandini considered only RPM and mud density, and inclination angle in his research. Most of the calculation cases are taken from Larsen's paper[2], but author took consideration on other variables as well.

8.1 Application of Larsen's correlation model

As it was presented earlier, Larsen developed a new design model that would predict the required critical transport fluid velocity for drilling in high angle holes from 55° to 90° degrees.

In order to perform the simulation of Larsen's experimental model, most of the variables are taken from Larsen experimental data set. During the simulation, only one parameter varies for each calculation. The values of the varying variable differ from Larsen's examples. The data used are as follows:

- YP=7(lbf/100ft^2)
- PV=7 (cp)
- ROP= 54 ft/hr
- Mud weight= 8,57 lbm/gal
- D_{cut}=0,175 in (Medium)
- D_{hole} =5 in
- D_{pipe}= 2,375 in
- Angle of Inclination = 55° to 90° degrees

MatLab codes that were used to draw graphs presented in this chapter are listed in Appendix B.

The values considered for the mud weight as a varying parameter are 10 ppg, 15 ppg, and 20 ppg instead of 8.57 ppg. The rest of the data set is constant as listed.

Figure (8.1.1) represents flow velocity in annulus versus pipe inclination, with *mud weight* as a varying parameter. The black dotted line represents flow velocity required for cuttings transport (CTFV), when mud weight is equal to 10 ppg, the red star line represents flow velocity (CTFV), when mud weight is equal to 15 ppg, and the blue triangles represents flow velocity (CTFV) when mud weight is equal to 20 ppg.

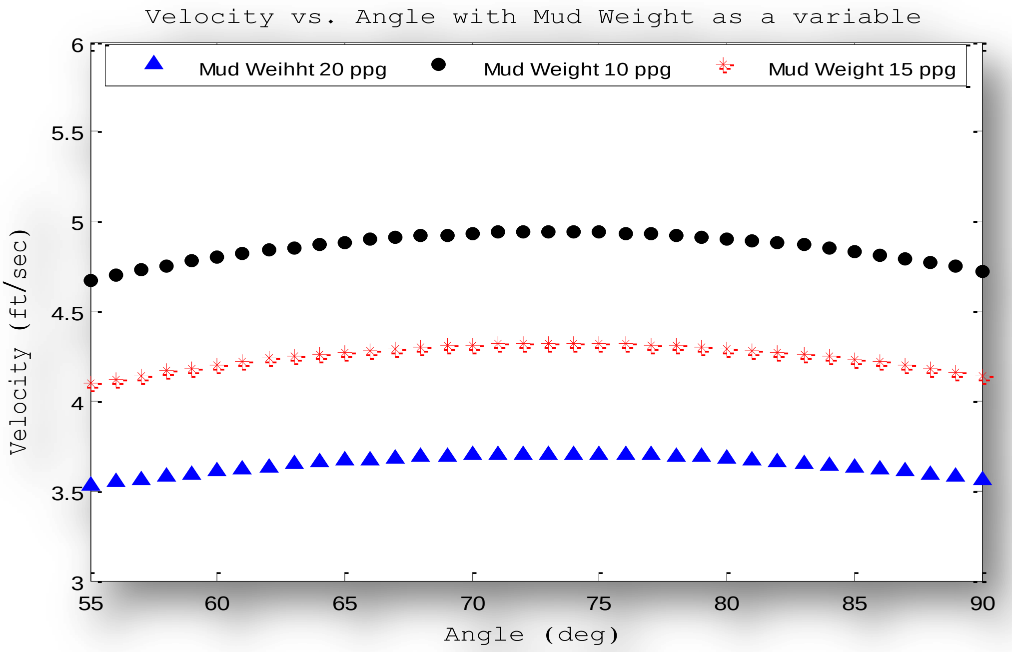


Figure (8.1.1): Flow velocity vs. angle when the mud weight is a variable parameter.

Figure (8.1.1) shows the relationship between the mud weights and required transport flow velocity (CTFV). Figure (8.1.1) indicates that with increasing mud weight, the flow velocity decreases. Therefore, cuttings transport improves at higher mud weight. Another important observation indicates that the flow velocity lines are curved at the angle between 65° and 80° degrees meaning that higher flow velocity is required to transport cuttings in this angle range. Moreover, the flow velocity with mud weight equal to 20 ppg (blue line) looks more linear compared to the black dotted line that is more curved. It seems that flow velocity (CTFV) with high mud weight is only slightly affected by inclination angle.

In the next figure, the values considered for ROP as a varying parameter are 30 ft/hr, 60 ft/hr, and 120 ft/hr instead of 54 ft/hr. The rest of data set is constant as listed previously.

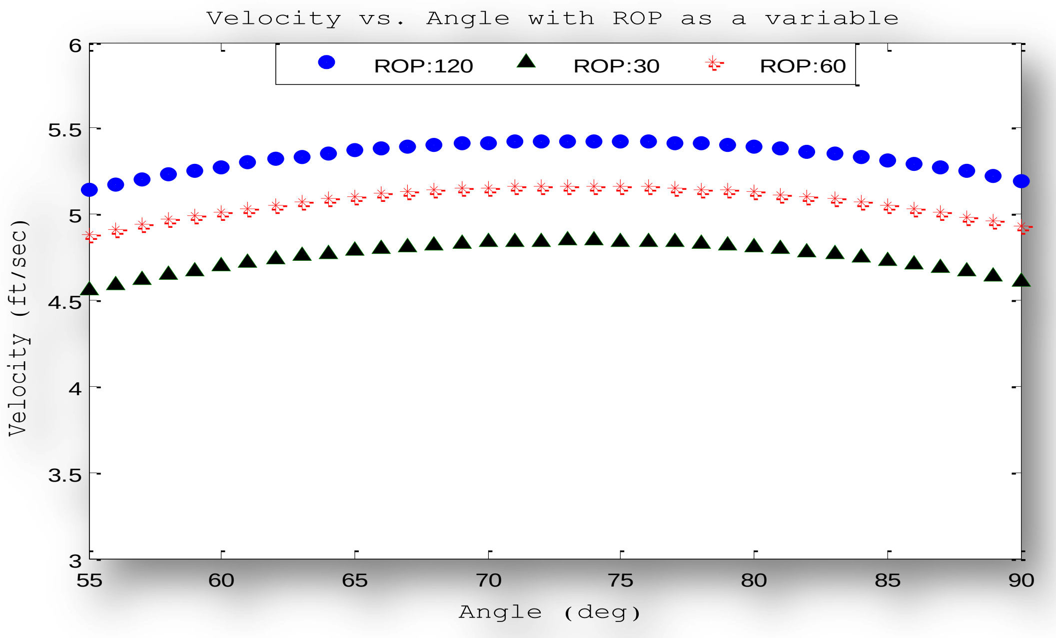


Figure (8.1.2): Flow velocity vs. angle of inclination with variation of ROP (ft/hr).

Figure (8.1.2) represents flow velocity in annulus versus angle of inclination, with ROP as a varying parameter. The black triangular line represents flow velocity (CTFV) with ROP equal to 30 ft/hr, the red star line stands for flow velocity with ROP equal to 60 ft/hr, while blue dotted line represents flow velocity with ROP equal to 120 ft/hr.

As observed from figure (8.1.2), higher ROP value requires higher flow velocity for cuttings transport, due to increase in cuttings concentration in annulus. As it was noticed in the previous figure, the flow velocity lines are slightly curved at the angle interval between 65° and 80° degrees.

Next, we consider the effect of *cuttings size* as a varying parameters. Cuttings size of 0, 1 inch, 0, 4 inch, and 0, 6 inch instead of 0, 175 inch was chosen for the simulation. The rest of data set is constant as listed during the simulation.

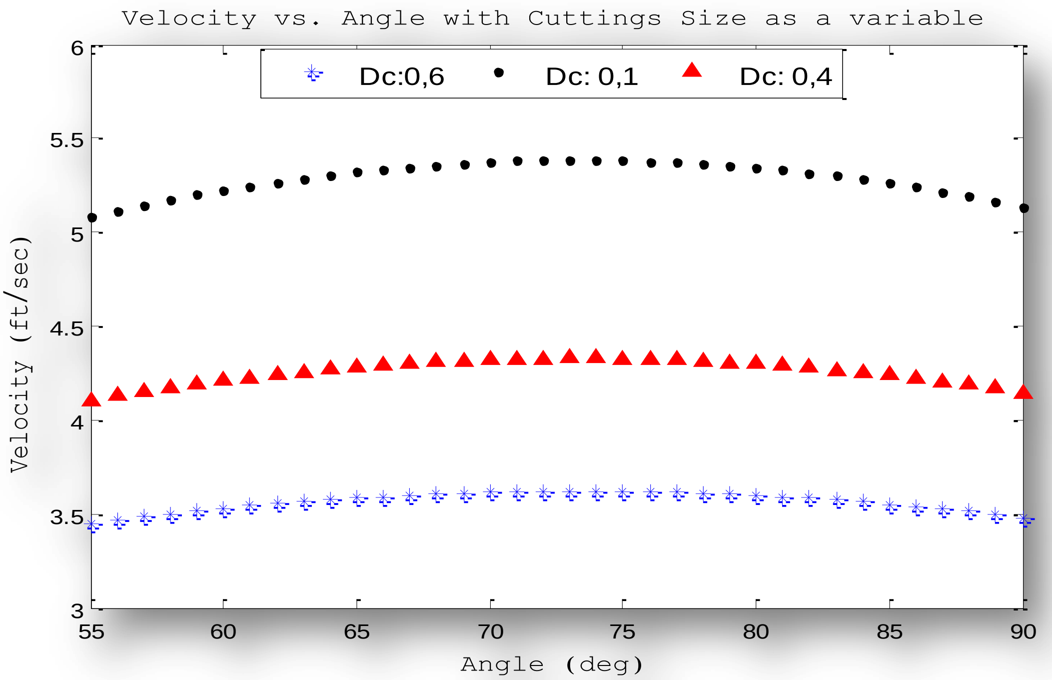


Figure (8.1.3): Flow velocity vs. angle of inclination with variation of cuttings size (inch).

Figure (8.1.3) shows required flow velocity in annulus versus angle of inclination, with *cuttings size* as a varying parameter. The black dotted line represents flow velocity with cuttings size equal to 0, 1" inch, the red triangle line stands for flow velocity with cuttings size equal to 0, 4" inch, while the blue star line represents flow velocity with cuttings size equal to 0, 6" inch.

Figure (8.1.3) shows the relationship between the cuttings size and the required cuttings transport flow velocity. From the observations, it is clear that smaller cuttings are more difficult to transport to surface since they require higher flow velocity than larger cuttings. This means that larger cuttings are easier to transport in inclined wellbore than smaller cuttings.

In figure (8.1.4), the considered values for *mud rheology* as varying parameters are 10, 15, and 20 instead of 7. The rest of data set is constant as listed during the simulation.

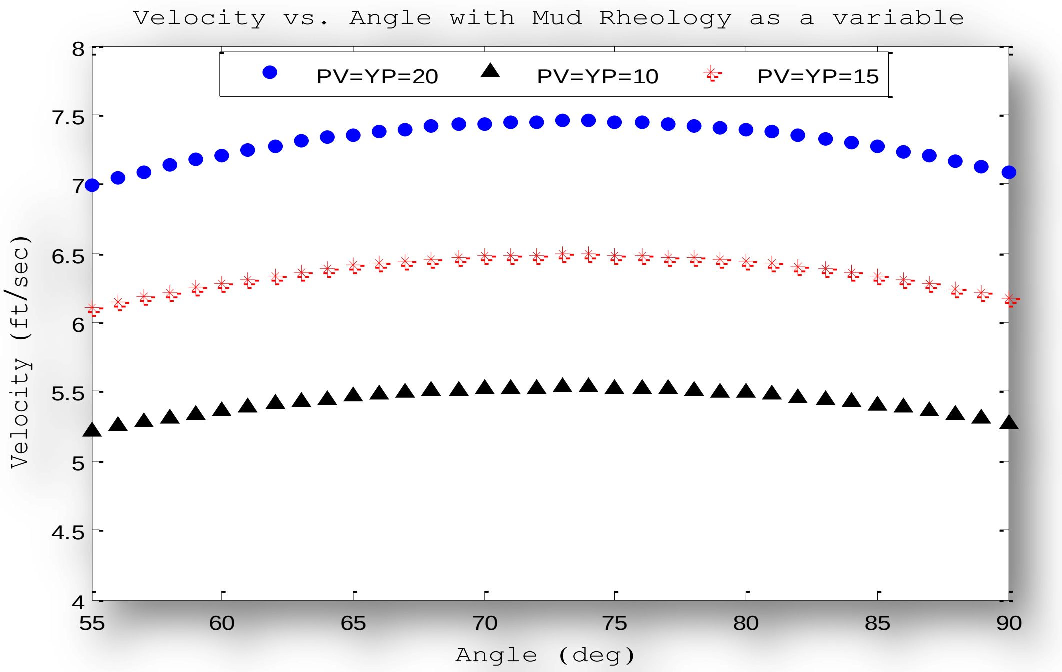


Figure (8.1.4): Flow velocity vs. angle of inclination with mud rheology as variable.

Figure (8.1.4) represents flow velocity (CTFV) in annulus versus angle of inclination, with *mud rheology* as a varying parameter. The black triangular line represents flow velocity with mud rheology with PV=10 (cp) and YP=10 (lbf/100ft^2), the red star line stands for flow velocity with mud viscosity PV=15 (cp) and YP=15 (lbf/100ft^2), the blue dotted line represents flow velocity with mud viscosity with PV=20 (cp) and YP=20 (lbf/100ft^2).

The graph indicates that in a horizontal wellbore, drilling fluid with lower mud rheology requires lower flow velocity for cuttings transport. This indicates that lower mud rheology improves cuttings transport.

The values considered for *drill-pipe diameter* as a varying parameter are 2,375 inch, 2,9 inch, and 3,4 inch (figure 8.1.5). The rest of data set is constant as listed during the simulation.

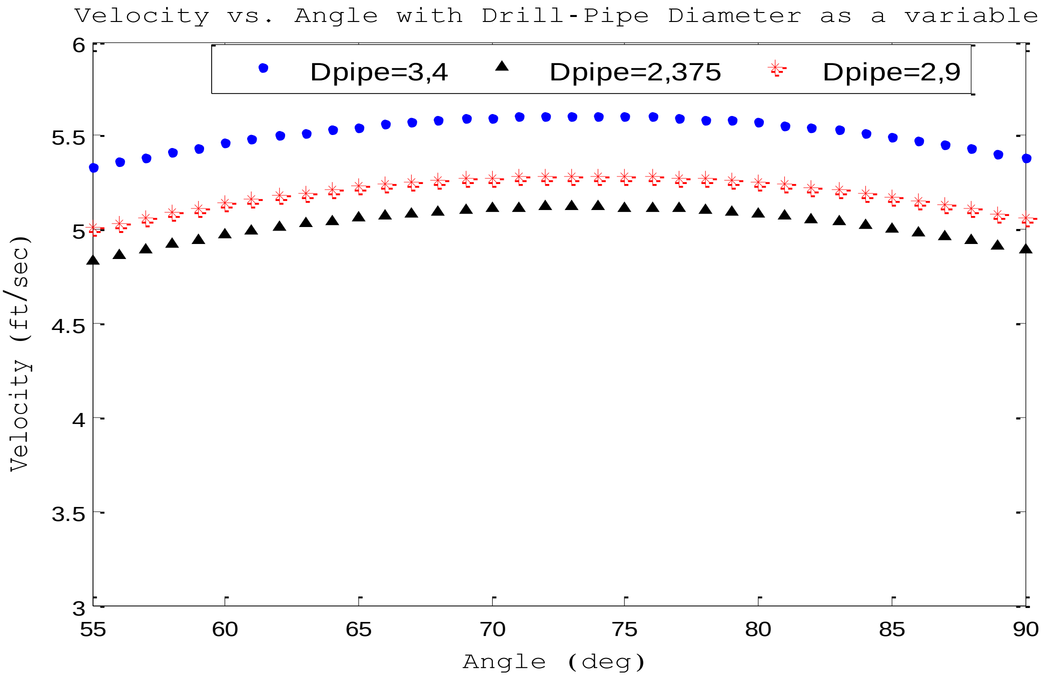


Figure (8.1.5): Flow velocity vs. angle of inclination when the drill-pipe diameter varies.

Figure (8.1.5) represents flow velocity (CTFV) in annulus versus angle of inclination, with *drill pipe diameter* as a varying parameter. The black triangle line represents flow velocity with drill pipe diameter equal to 2, 375” inch, the red star line stands for flow velocity with drill pipe diameter equal to 2, 9” inch, while the blue dotted line represents flow velocity with drill pipe diameter equal to 3, 4” inch.

As it is observed from the graph, larger drill pipe diameter (smaller annular areal) requires higher flow velocity for cuttings transport. Note that Larsen et al.[2], in their examples, did not perform experiments with different pipe geometry.

8.2 Application of Rubiandini’s correlation model

Rubiandini’s model can be used for inclination angles between 0° and 90° degrees. As it was presented earlier, Rubiandini used Moore’s slip velocity developed for vertical wellbore in his research so that it would be applicable for inclined wellbore. In addition, he introduced correction factors for different physical variables, based on the results from Larsen’s[4] model and Peden’s work to calculate the minimum transport velocity (V_{min}). Note that Moore’s model is taken from Rubiandini’s paper[5]. MatLab codes used to draw the various graphs that are presented in Appendix C.
In order to use Rubiandini’s model, the same data set are used. These data are the following:

- YP=7 (lbf/100ft^2)
- PV=7 (cp)
- RPM= 80

- ROP= 54 ft/hr
- Mud weight= 8,57 lbm/gal
- D_{cut}=0,175 in (Medium)
- D_{hole} =5 in
- D_{pipe}= 2,375 in
- Angle of Inclination = 0° to 90° degrees
- Bed Porosity= 36 %
- $\rho_{cuttings}$ = 19 (lbs/gal)

During the simulation, only one parameter varies for each calculation. The values of the varying variables differ from those that were used by Larsen et al.[2]

Figure (8.2.1) presents minimum flow velocity versus angle of inclination, with *mud weight* as a varying parameter. These varying parameters are 10 ppg, 15 ppg, and 20 ppg instead of 8, 57 ppg. The rest of data set is constant as listed above.

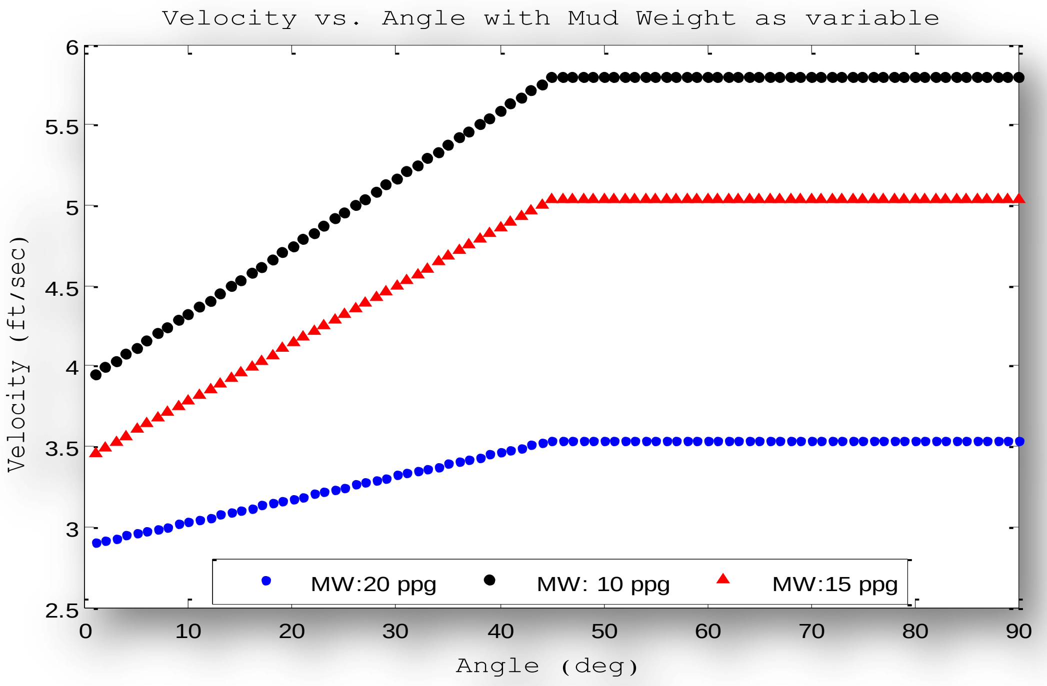


Figure (8.2.1): Minimum flow velocity vs. angle of inclination when the mud weight varies.

The black dotted line represents flow velocity with mud weight equal to 10 ppg, the red dotted line stands for flow velocity with mud weight equal to 15 ppg, while the blue dotted line represents flow velocity with mud weight equal to 20 ppg.

This model shows the same tendency as it was observed by using Larsen's model, namely that when the mud weight increases, the flow velocity decreases. Therefore, cuttings transport improves at higher mud weight. Another observation is that the flow velocity lines are constantly increasing up to 45° degrees. In the range from 45° to 90° degrees, the flow velocity is constant.

We observe that for high mud weight, there is no large difference for required minimum flow velocity in the horizontal versus the vertical sections. This shows that a high mud weight improves cuttings transport in the inclined wellbores.

Next, we consider ROP as a varying parameter. These parameters are 30 ft/hr, 60 ft/hr, and 120 ft/hr instead of 54 ft/hr. The rest of data set is constant as listed previously.

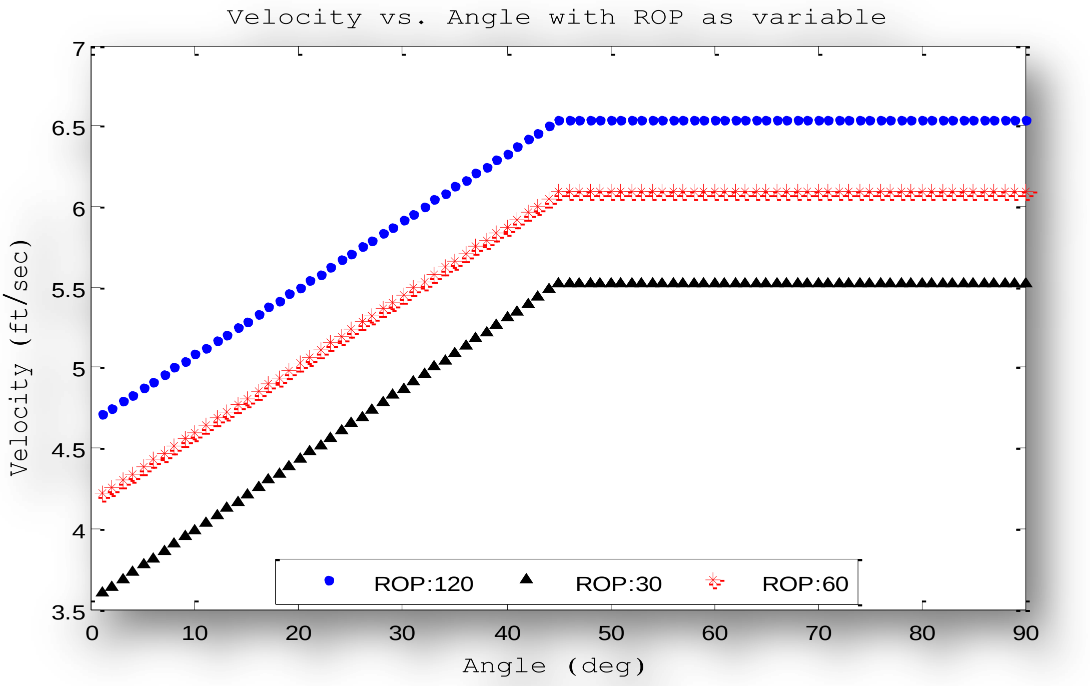


Figure (8.2.2): Minimum flow velocity versus angle of inclination when the ROP (ft/hr) varies.

Figure (8.2.2) represents flow velocity in annulus versus angle of inclination, with *ROP* as a varying parameter. The black triangle line represents flow velocity with ROP equal to 30 ft/hr, the red line stands for flow velocity with ROP equal to 60 ft/hr, while the blue dotted line represents flow velocity with ROP equal to 120 ft/hr.

By comparing these three lines, it is observed that higher ROP value requires higher transport flow velocity, due to increase in cuttings concentration in annulus. Minimum flow velocity lines are constantly increasing up to 45° degrees and in the range from 45° to 90° degrees, the required minimum flow velocity is unchanged.

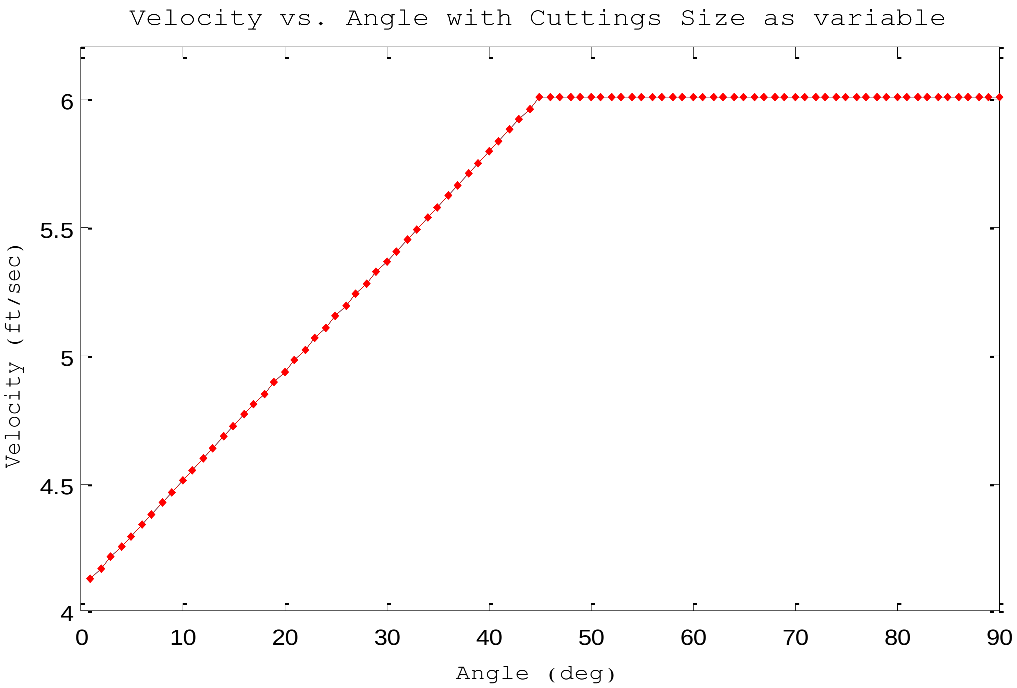


Figure (8.2.3): Minimum flow velocity vs. angle of inclination when the cuttings size varies.

Figure (8.2.3) represents flow velocity in annulus versus angle of inclination, with *cuttings size* as a varying parameter. The red dotted line represents flow velocity with cuttings size equal to 0, 1; 0, 4; 0, 6 inch. These values were used in predictions using Larsen's model and are taken for comparison. As seen from the graph, all three curves overlap each other. This means that Rubiandini's model does not show any variation in predicted velocity when the size of the smaller cuttings is varying. Therefore, in the next graph (8.2.4), the author chooses cuttings size values that were more spread in order to represent the relation between the cuttings size and the predicted transport flow velocity.

The values considered for cuttings size as a varying parameter are 0, 09 inch, 0, 9 inch, 1 inch instead of 0, 175 inch.

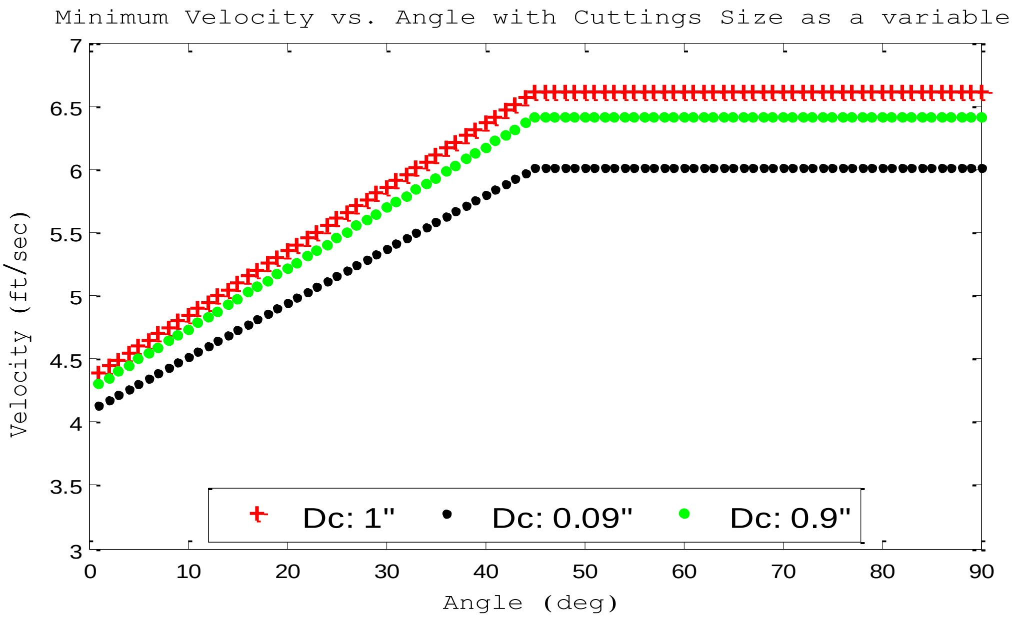


Figure (8.2.4): Minimum flow velocity vs. angle of inclination when the cuttings size varies.

Figure (8.2.4) represents flow velocity in annulus versus angle of inclination, with *cuttings size* as a varying parameter. The black dotted line represents flow velocity with cuttings size equal to 0, 09 inch, the green dotted line stands for flow velocity with cuttings size equal to 0, 9 inch, while the red line represents flow velocity with cuttings size equal to 1 inch.

Figure (8.2.4) shows the relation between the cuttings size and the transport flow velocity. This model predicts that larger cuttings are more difficult to transport to surface since they require higher flow velocity than smaller cuttings. This observation shows total disagreement with Larsen’s model results. The main reason is that Rubiandini’s model is based on Moore’s model. In this model, cuttings size is a parameter. However, Rubiandini did not included correction factors for cuttings size as Larsen did in his model.

In general, earlier experiments suggest that smaller cuttings are more difficult to transport. However, observations from this figure (8.2.4) contradict this.

Next, we consider *mud rheology* as a varying parameter. The values considered for mud rheology as a varying parameter are PV=10 (cp), YP=10 (lbf/100ft^2), PV=15 (cp), YP=15 (lbf/100ft^2) and PV=20 (cp), YP=20 (lbf/100ft^2), instead of PV=7 (cp), YP=7 (lbf/100ft^2).

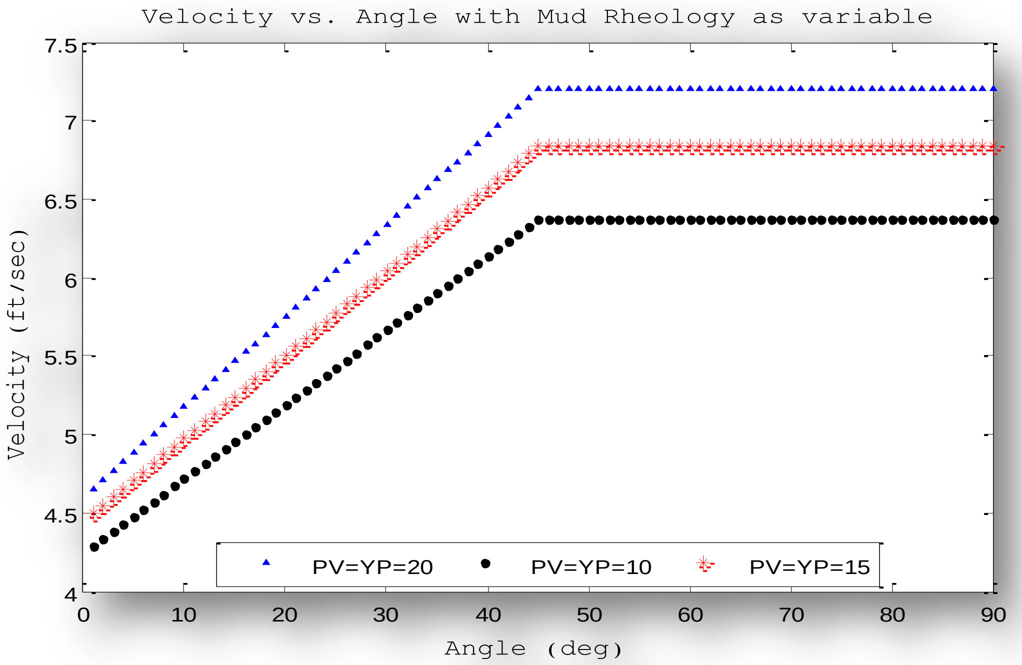


Figure (8.2.5): Minimum flow velocity vs. angle of inclination when the mud rheology varies.

Figure (8.2.5) represents flow velocity in annulus versus angle of inclination, with *mud rheology* as a varying parameter. The black dotted line represents flow velocity with mud rheology with PV=10 (cp) and YP=10 (lbf/100ft^2), the red line stands for flow velocity with mud rheology PV=15 (cp) and YP=15 (lbf/100ft^2), and the blue line represents flow velocity with mud rheology with PV=20 (cp) and YP=20 (lbf/100ft^2).

The graph indicates that drilling fluid with high mud rheology requires higher transport flow velocity. According to figure (8.2.5), drilling fluid with low mud rheology should be recommended for sufficient cutting transport.

Then, we consider *RPM* as a varying parameter. Rubiandini, in his model, took into account the effect of RPM. The values considered for RPM as a varying parameter are 80, 100, 120, 150, and 180 instead of 80. The rest of data set is constant as listed during the simulation.

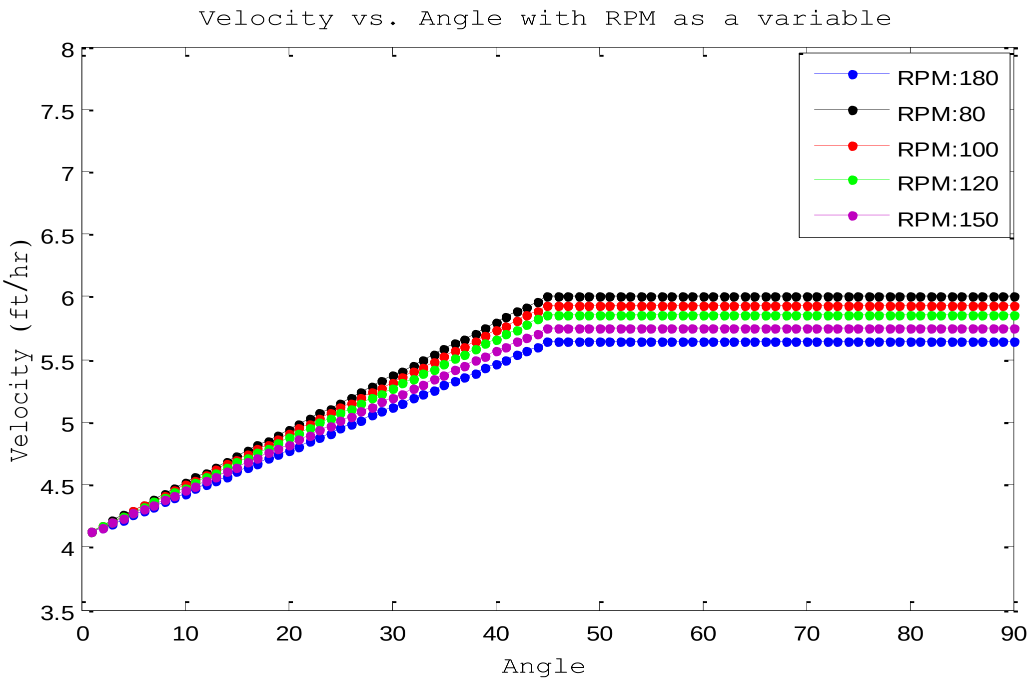


Figure (8.2.6): Minimum flow velocity vs. angle of inclination with RPM as a variable.

Figure (8.2.6) represents flow velocity in annulus versus angle of inclination, with *RPM* as a varying parameter. The black line represents flow velocity with RPM equal to 80, the red line represents flow velocity with RPM equal to 100, the green line represents flow velocity with RPM equal to 120, the violet line stands for flow velocity with RPM equal to 150, and blue line represents flow velocity with RPM equal to 180.

Observation shows that all graphs start at the same flow velocity value (4,1 (ft/hrs)), which corresponds to Moore's vertical model and graphs have the same trend.

It RPM is known to have impact on cuttings transport as seen in previously published observations. Figure (8.2.6) shows that higher RPM values improve the cuttings transport process, since lower minimum flow velocity is predicted.

Figure (8.2.7) consider *drill-pipe diameter* as a varying parameter. These varying parameters are 2,375 inch, 2,9 inch, 3,4 inch instead of 2,375 inch.

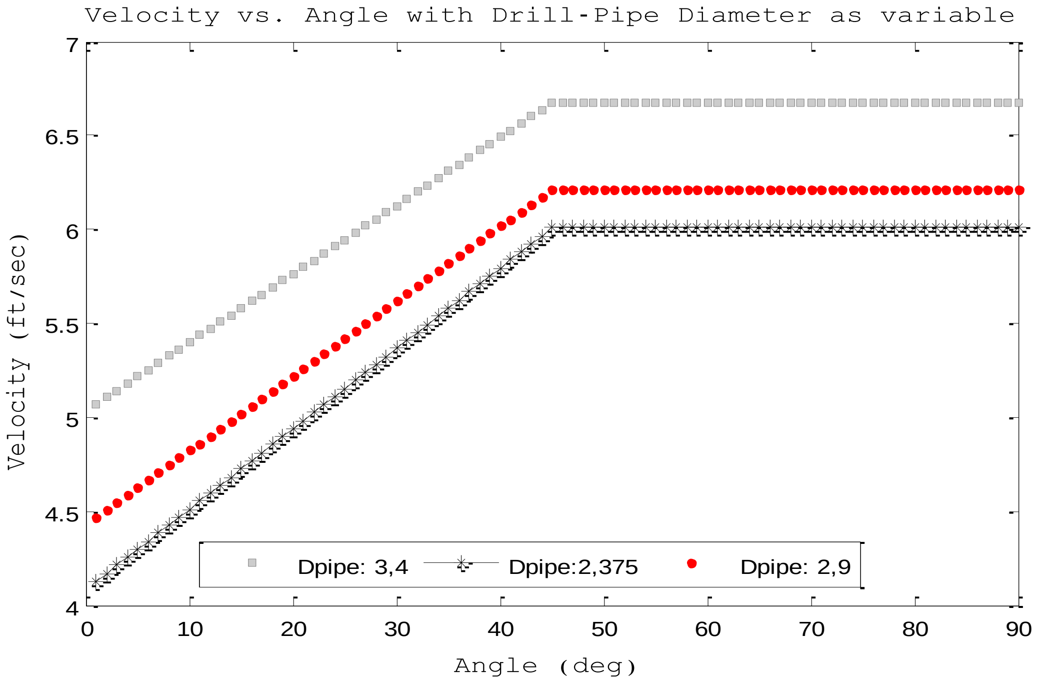


Figure (8.2.7): Minimum flow velocity vs. angle of inclination with drill-pipe diameter as a variable.

Figure (8.2.7) shows required flow velocity in annulus versus angle of inclination, with *drill pipe diameter* as a varying parameter. The black line represents flow velocity with drill pipe diameter equal to 2,375” inch, the red dotted line stands for flow velocity with drill pipe diameter equal to 2,9” inch, while the gray dotted line represents flow velocity with drill pipe diameter equal to 3,4” inch.

As seen from the graph, increasing pipe diameter leads to increase in flow velocity showing the same trend as the Larsen’s model. The model considers the geometry in the same way.

8.3 Predictions' of required flow rates using an example well

In this section, we calculate the required flow rate using Larsen's and Rubiandini's for an example well. The calculations were based on data set close to a practical drilling situation: 8 ½" section well, which is drilled with a 5" drill pipe. It is noticed that this well geometry is different from the experimental data used by Larsen. This well consists of both vertical and horizontal sections. The horizontal section is inclined up to 90° degrees. In this section, it is common to use a flow rate in the range from 1500 to 2000 l/min.

The purpose of these calculations is to find out whether Larsen and Rubiandini's models give values corresponding to the typical flow rates seen in practice (1500 -2000 l/min).

For this simulation and calculations, these drilling parameters are kept constant:

- Dpipe=5 (inch)
- Dhole=8.5 (inch)
- ROP=33 (ft/hr)
- PV=7 (cp)
- YP=7 (lbf/100ft^2)
- Dcutt=0.3 (inch)
- Mud weight =10.83 (ppg)
- RPM = 80
- Cuttings density = 19 lbs/gal

In the simulations, the following variables were used for both Larsen's and Rubiandini's models and only one of these parameters is varying in each simulation:

ROP (ft/h)	33	98,3	164
Mud Weight (ppg)	10,83	12,5	15
Cuttings Size (inch)	0,1	0,3	0,6
Mud Rheology (YP=PV)	7	10	15

8.3.1 Predictions of required flow rate using Larsen's model:

Graphs presented in this chapter are drawn using MatLab codes that are listed in Appendix D.

Figure (8.3.1.1) represents *ROP* as a varying parameter.

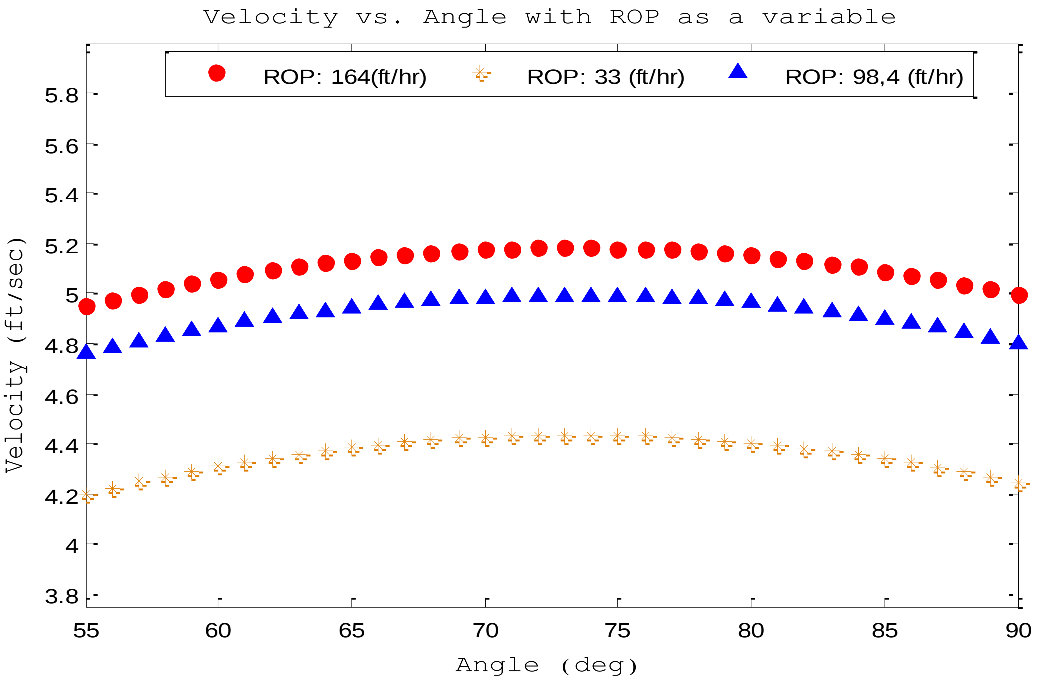


Figure 8.3.1.1: Flow Velocity vs. angle of inclinations with ROP as a variable.

In figure (8.3.1.1), three different ROP value were used. The orange star line represents required flow velocity with ROP equal to 33 (ft/hr) [10 m/hr]. The blue triangle line represents required flow velocity with ROP equal to 98,4 (ft/hr) [30 m/hr], and on the top is red dotted line that represents required flow velocity with ROP equal to ROP 164 ft/hr [50m/hr]. This figure demonstrates that higher ROP requires higher flow velocity for effective cuttings transport.

By using equation (8.3.1.1) below, it is possible to calculate annulus area.

$$A = \frac{\pi}{4}\left[(D_{hole} * 0.0254)^2 - \left(D_{pipe} * 0.0254\right)^2\right] \ (m^2) \text{ ....(8.3.1.1)}$$

Equation for flow rate is expressed in units:

$$Q({m^3}/{s}) = V({m}/{s}) * A(m^2) \text{ ....(8.3.1.2)}$$

For ROP value equal to 33 (ft/hr) or (10 m/h) the results show:

- At inclination angle of 55° degrees, flow velocity is equal to 4.2 (ft/sec) or 1, 28 (m/sec). By using equations (8.3.1.1) and (8.3.1.2), the required flow rate for cuttings transport is 1839 (l/min).

- At inclination angle 75° degrees, flow velocity is equal to 4,45 (ft/s). This corresponds to a flow rate of 1948 (l/min).
- At the inclination angle 90° degrees, flow velocity is equal to 4,23 (ft/s). This corresponds to a flow rate equal to 1848 (l/min).

Calculations of flow rate for the other two ROP curves are represented in table 8.3.1.1:

Flow Rate	Flow Rate (l/min)	Flow Rate (l/min)	Flow Rate (l/min)
Inclination (degrees)	55˚	75˚	90˚
ROP: 10 (m/hr) 33 (ft/hr)	1839	1948	1848
ROP: 30 (m/hr) 98,4 (ft/hr)	2080	2167	2101
ROP: 50 (m/hr) 164 (ft/hr)	2167	2255	2189

Table 8.3.1.1: Calculations of flow rate at different inclinations with ROP as a variable.

By analyzing value in table (8.3.1.1), it is obvious that the required flow rate is highest at inclination angle of 75˚ degrees. The second observation indicates that with increasing ROP, the flow rate has to be increased as well.

By drilling with ROP equal to 10 m/hr, required flow rate values are within the range of the typical flow rate of 1500-2000 l/min, whereas for the other two ROP values, the required flow rate is beyond this range.

Next, we consider *mud weight* as a varying parameter.

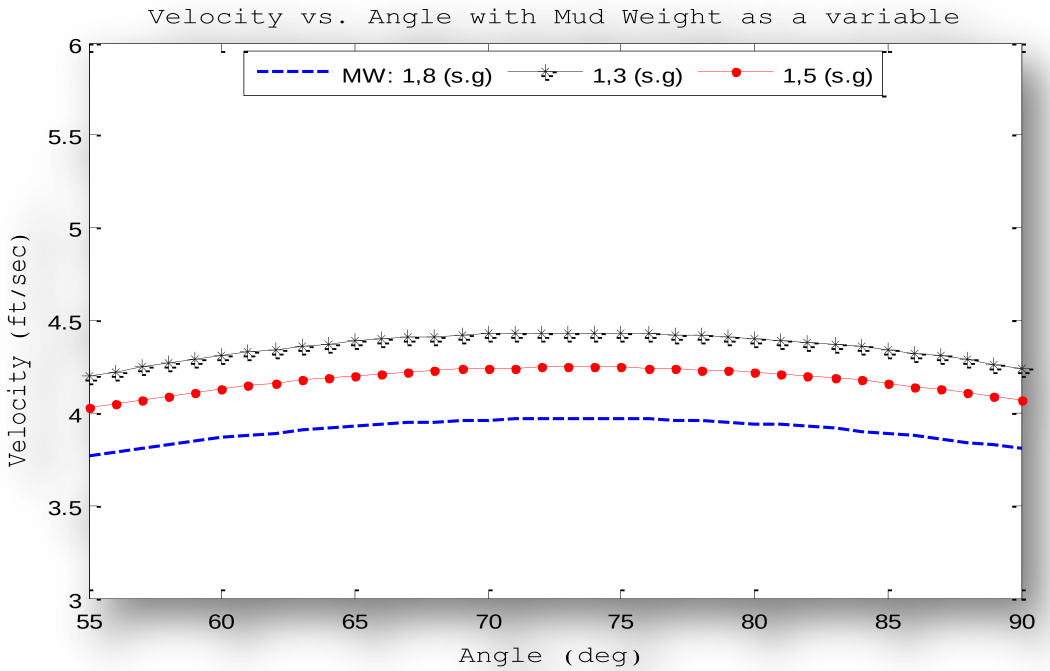


Figure 8.3.1.2: Flow velocity vs. angle of inclination with mud weight as a variable.

Figure (8.3.1.2) shows required flow velocity versus angle of inclination with mud weight as a variable.

For mud weight value equal to 1,8 (s.g) or 15(ppg) the result show:

- At inclination angle of 55° degrees, required flow velocity is equal to 3,55 (ft/sec) or 1,08 (m/sec). By using equations (8.3.1.1) and (8.3.1.2), the required flow rate for cuttings transport is 1554 (L/min).
- At inclination angle 75° degrees, flow velocity is equal to 3,59 (ft/s). Required flow rate is then 1572 (l/min).
- At the inclination angle 90° degrees, required flow velocity is equal to 3,56 (ft/s). This corresponds to a flow rate of 1563 (l/min).

Calculations of flow rate for other two mud weight curves are represented in table 8.3.1.2:

Flow Rate	Flow Rate (l/min)	Flow Rate (l/min)	Flow Rate (l/min)
Inclination (degrees)	55°	75°	90°
Mud Weight: 1,3 (sg), 10,83 (ppg)	1839	1926	1883
Mud Weight: 1,5 (sg), 12,5 (ppg)	1751	1839	1773
Mud Weight: 1,8 (sg), 15 (ppg)	1554	1572	1563

Table 8.3.1.2: Calculations of flow rate at different inclinations with mud weight as a variable.

The table above demonstrates again that higher mud weight is more favorable for cuttings transport, since a lower flow rate is required. Inclination angle of 75° degrees requires the highest flow rate for cutting transport. Notice that all flow rate values are within the typical range of typical flow rate values (1500 - 2000 l/min).

Next, we consider *cuttings size* as a varying parameter.

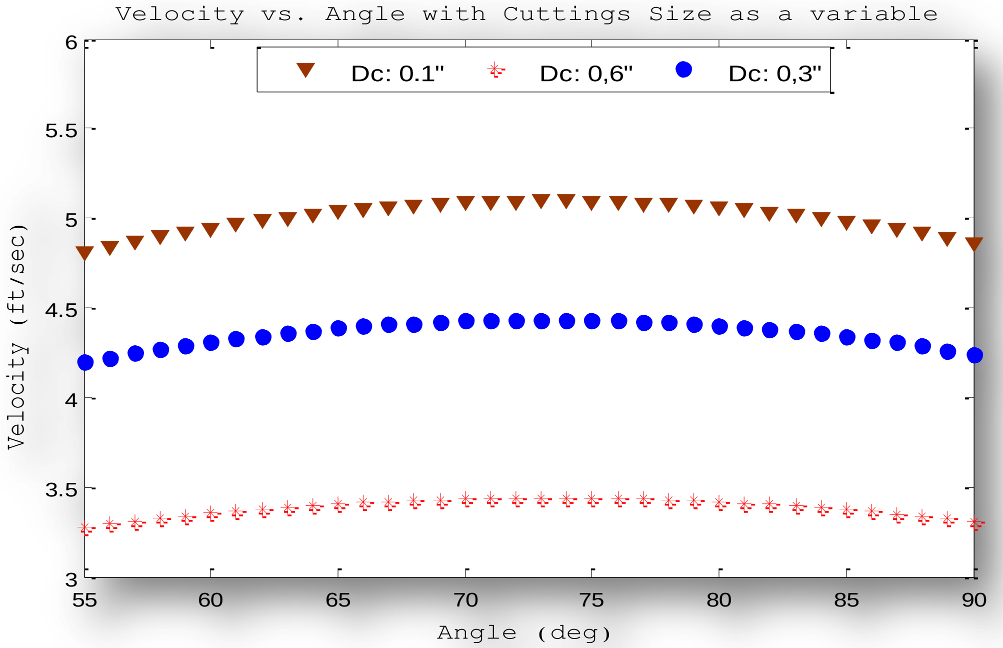


Figure 8.3.1.3: Flow velocity vs. angle of inclinations with cuttings size as a variable.

Figure (8.3.1.3) shows required flow velocity versus angle of inclination with cuttings size as a variable.

For largest cuttings size value equal to 0, 6 “or 1,524 cm, the results show:

- At inclination angle of 55° degrees, required flow velocity is equal to 3, 25 (ft/sec) or 0, 99 (m/sec). By using equations (9.3.1.1) and (9.3.1.2), the required flow rate for cuttings transport is 1423 (l/min).
- At inclination angle 75° degrees, flow velocity is equal to 3, 48 (ft/s). Required, flow rate is then 1510 (l/min).
- At the inclination angle 90° degrees, flow velocity is equal to 3, 26 (ft/s). This corresponds to a flow rate of 1489 (l/min).

Calculations of required flow rate for the other mud weight curves are represented in table 8.3.1.3:

Flow Rate	Flow Rate (l/min)	Flow Rate (l/min)	Flow Rate (l/min)
Inclination (degrees)	55°	75°	90°
Cuttings Size: 0,1”, (0,254 cm)	2102	2189	2123
Cuttings Size: 0,3”, (0,76 cm)	1859	1948	1883
Cuttings Size: 0,6”, (1,524 cm)	1423	1510	1489

Table 8.3.1.3: Calculations of flow rate at different inclinations with cuttings size as a variable.

Table (8.3.1.3) demonstrates that smaller cuttings are more difficult to transport since they require higher flow rate than the bigger ones. At the inclination angle of 75° degrees, the required flow rate has the highest value. Here, all the required flow rate values are within the range of the typical flow rate of 1500-2000 l/min.

Then, we consider *mud rheology* as a varying parameter.

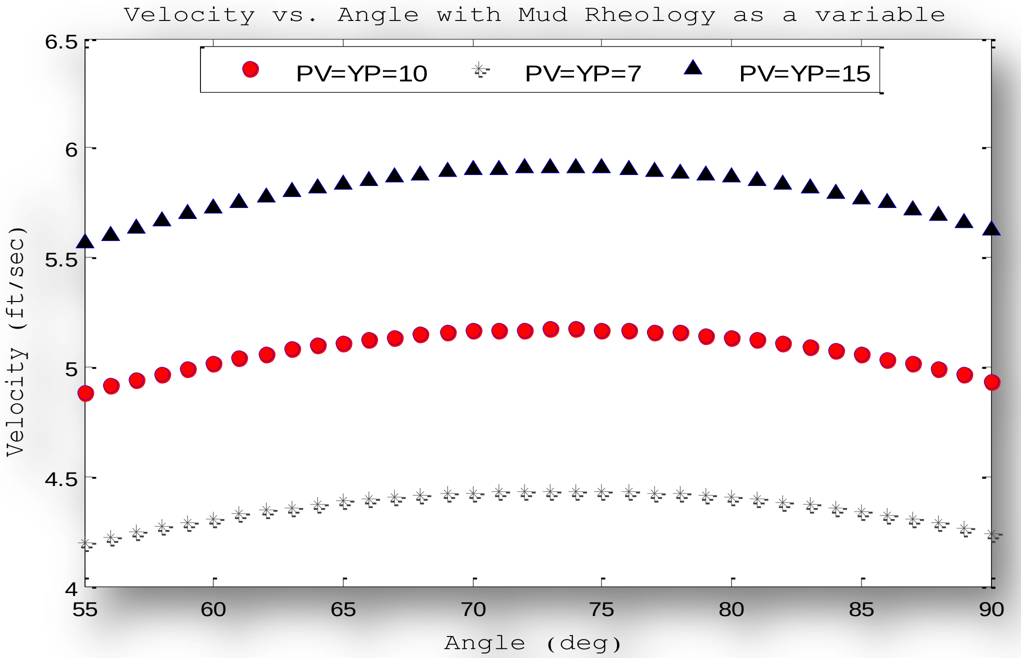


Figure 8.3.1.4: Flow velocity vs. angle of inclinations with mud rheology as a variable.

Figure (8.3.1.4) represents the required flow velocity versus angle of inclination with mud rheology as a variable.

For lowest mud rheology value equal to PV=7 (cP), PY=7 (lbf/100ft^2), we can observe:

- At inclination angle of 55° degrees, required flow velocity is equal to 4,2 (ft/sec) or 1,28 (m/sec). By using equations (8.3.1.1) and (8.3.1.2), the required flow rate for cuttings transport is 1839 (l/min).
- At inclination angle 75° degrees, the required flow velocity is equal to 4,45 (ft/s). The required flow rate is then equal to 1966 (l/min).
- At the inclination angle 90° degrees, flow velocity is equal to 4,3 (ft/s). This corresponds to a required flow rate of 1857 (l/min).

Flow Rate	Flow Rate (l/min)	Flow Rate (l/min)	Flow Rate (l/min)
Inclination (degrees)	55°	75°	90°
Mud Rheology: PV=PY=7	1839	1966	1857
Mud Rheology: PV=PY=10	2137	2277	2158
Mud Rheology: PV=PY=15	2434	2443	2465

Table 8.3.1.4: Calculations of flow rate at different inclinations with mud rheology as a variable.

Table (8.3.14) demonstrates that mud rheology affects cuttings transport considerably. For low mud rheology (PV=PY=7), the required flow rate values are within the range of the typical flow rate of 1500-2000 l/min. It is also observed that at increasing mud viscosity, the predicted required flow rate becomes quite large. This shows again that low mud rheology is effective for cuttings transport.

8.3.2 Predictions of required flow rate using Rubiandini's model:

As it was mentioned earlier in chapter 8.3, these predictions are performed using the same drilling parameters as in the Larsen's predictions for required flow rate in the example well (chapter 8.3.1). Graphs are drawn using MatLab codes that are presented in Appendix E.

Figure below (8.3.2.1) shows the predicted flow rate required with *ROP* as a variable parameter when using Rubiandini's model.

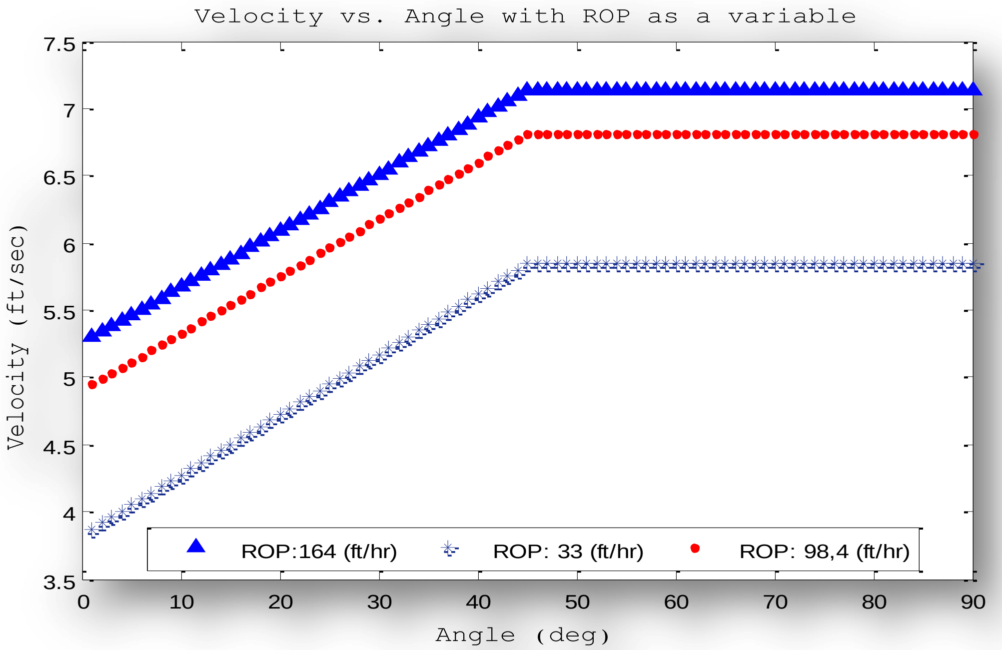


Figure 8.3.2.1: Flow velocity vs. angle of inclination with ROP as a variable.

As it is indicated in the figure (9.3.2.1) at low ROP, 33 ft/hr or 10 m/hr, the following observations are made:

- At inclination angle of 0° degrees, the required flow velocity value is equal to 3,9 (ft/sec) or 1,19 (m/sec). This value corresponds to the vertical wellbore, which is represented by Moore's model. By using equations (9.3.1.1) and (9.3.1.2), the required flow rate for cuttings transport is 1664 (l/min).
- At inclination angle between 45° to 90° degrees, the flow velocity is constant and it equals to 5,8 (ft/s). This corresponds to a flow rate of 2539 (l/min).

Calculations of flow rate for two other ROP values are represented in table 8.3.2.1:

Flow Rate	Flow Rate (l/min)	Flow Rate (l/min)
Well Section	Vertical, (0° degree) (Moore's vertical model)	Horizontal (45° to 90° degrees)
ROP: 33 (ft/hr), 10 (m/hr)	1664	2539
ROP: 98,4 (ft/hr), 30 (m/hr)	2145	2984
ROP: 164 (ft/hr), 50 (m/hr)	2320	3124

Table 8.3.2.1: Calculations of required flow rate at vertical and horizontal sections with ROP as a variable.

Table (8.3.2.1) demonstrates that higher ROP requires higher flow rate for cuttings transport. It is observed that the predicted required flow rates are quite large compared to the typical flow rate (1500-2000 l/min) that is used in the 8 ½" section wellbore.

Figure (8.3.2.2) shows the prediction of required flow velocity versus angle of inclination with *mud weight* as a variable parameter.

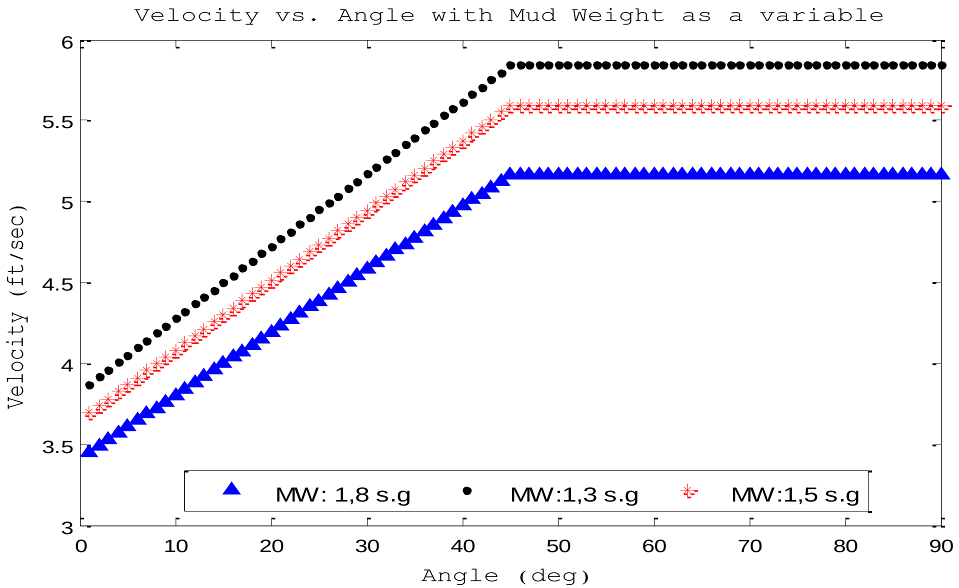


Figure 8.3.2.2: Flow velocity vs. angle of inclination with mud weight as a variable.

From the figure (8.3.2.2), with the high mud weight equal to 1,8 sg or 15 ppg, the following observations are made:

- At inclination angle of 0° degrees, the flow velocity is equal to 3,48 (ft/sec) or 1,06 (m/sec). This corresponds to a required flow rate equal to 1524 (l/min).
- At inclination angle between 45° to 90° degrees, the flow velocity is constant and it equals to 5,2 (ft/s). This corresponds to a flow rate equal to 2233 (l/min).

Predicted flow rate required for the other two mud weights are shown in the table 8.3.2.1:

Flow Rate Well Section	Flow Rate (l/min) Vertical (0° degrees) (Moore's vertical model)	Flow Rate (l/min) Horizontal (45° to 90° degrees)
Mud Weight: 1,3 (s.g) or 10,83 ppg	1707	2539
Mud Weight: 1,5 (s.g) or 12,5 ppg	1620	2447
Mud Weight: 1,8 (s.g) or 15 ppg	1524	2233

Table 8.3.2.2: Calculations of required flow rate at vertical and horizontal sections with mud weight as a variable.

Table (8.3.2.2) confirms that increasing mud weight is good for improving cuttings transport. It is observed that the predicted flow rate for ensuring cuttings transport in the horizontal section is quite large and exceeds the typical flow rate used when drilling the 8 ½" section. For the vertical case, the predicted flow rate required seems to be more normal.

As it was observed in chapter 8.2, the Rubiandini's model gives contradictive predictions on required flow velocity when cuttings size is varied. For this reason, it was decided not to consider cuttings size here.

Figure (8.3.2.3) represents Rubiandini's model prediction for flow velocity versus angle of inclination with *mud rheology* as a variable parameter.

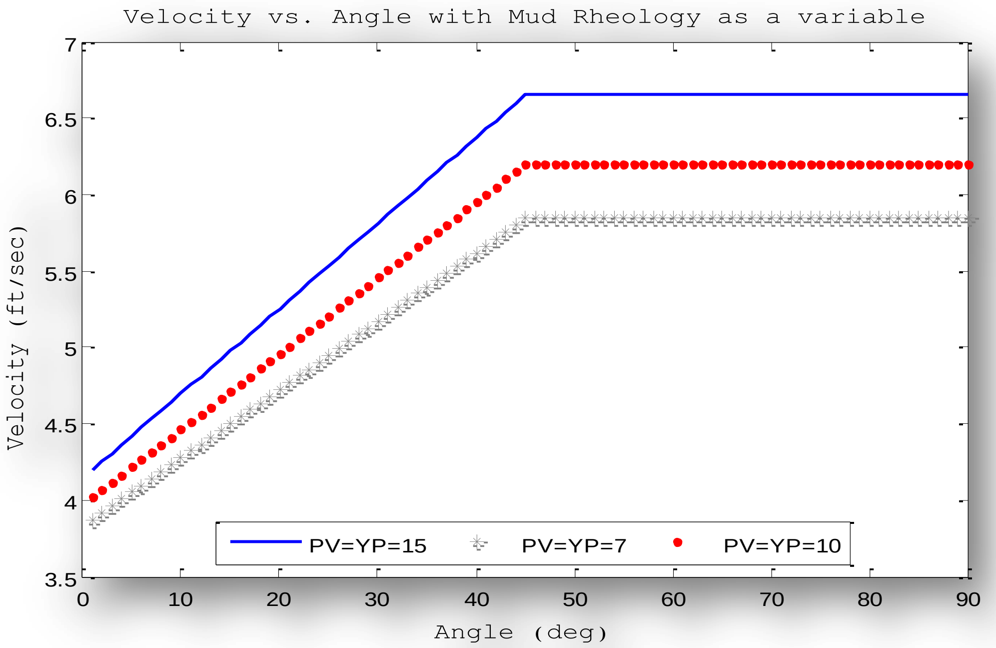


Figure 8.3.2.3: Flow velocity vs. angle of inclination with mud rheology as a variable.

Figure (8.3.2.3) illustrates that at low mud rheology PV= 7 (cP) and YP= 7 (lbf/100ft^2), the following observation can be made:

- At inclination angle of 0° degrees, the required flow velocity is equal to 3, 8 (ft/sec) or 1, 16 (m/sec). Then the required flow rate for cuttings transport is equal to 1664 (l/min).
- At inclination angle between 45° to 90° degrees, the required flow velocity is constant and equals to 5,8 (ft/s). This corresponds to a flow rate of 2557 (l/min).

Calculations of flow rate for the other two mud rheology values are represented in table 8.3.2.3:

Flow Rate	Flow Rate (l/min)	Flow Rate (l/min)
Well Section	Vertical, (0° degree) (Moore's vertical model)	Horizontal (45° to 90° degrees)
Mud Rheology: PV=PY=7	1664	2557
Mud Rheology: PV=PY=10	1751	2714
Mud Rheology: PV=PY=15	1839	2911

Table 8.3.2.3: Calculations of required flow rate at vertical and horizontal sections with mud rheology as a variable.

As discussed before, the model predicts that large mud rheology parameters lead to an increase in required flow rate for cuttings transport. Both this model and Larsen' model show this tendency.
Again, it is observed that the predicted flow rate in the horizontal section is quite large compared to what is seen in practice.

As observed from table (8.3.2.3), all flow rate values in the vertical well section are inside the range of typical flow rate values (1500 - 2000 l/min). However, for the horizontal section, the predicted rates are much larger than expected.

9. DISCUSSION

Cuttings transport is one of the major problems during drilling operations. After so many years with research and investigation about these phenomena, there is still lacking a complete understanding of the cuttings transport process, and hole cleaning is still an operational challenge.

The literature review revealed that the most extensive research on cuttings transport and hole cleaning in inclined and horizontal wellbore was done during the 80's and 90's. A number of scientists believed that drillings parameters, mud rheological parameters and other factors, like annular flow velocity, particle size and flow regimes affected the transportation of the cuttings through the wellbore and therefore performed a broad study on the subject. In recent years, only few papers have been presented focusing on mud additives and its influence on the hole cleaning.

As it was mentioned earlier, cuttings transport investigations are categorized by two main approaches, namely empirical and mechanistic approaches. The majority of scientists used the empirical approach in order to develop prediction models for fluid flow velocity necessary to transport cuttings in an effective way. A group of investigators developed two- and three-layer models using the mechanistic approach.

In this thesis, both approaches were presented. The empirical models of Larsen, Peden, and Rubiandini were discussed in details, while Kamp's and Gavignet's models based on the mechanistic approach were presented in order to illustrate the complexity of this approach. Later, Larsen's empirical model was compared with Rubiandini's model in two ways. First, by using Larsen's experimental data set in applying both for Larsen's and Rubiandini's models to establish the effect of various drilling parameters on cuttings transport. Then, by calculating flow rate using the practical drilling data from 8 ½" well section, the Larsen's and Rubiandini's models were compared once again. The differences between these two models are discussed in chapter 9.1 and 9.2.

9.1 Comparison of Larsen's and Rubiandini's models using Larsen's experimental data set

In this chapter, results from Larsen's model are compared with results that were achieved from Rubiandini's model by using the data set from Larsen's experiments. The predictions from these models were presented in chapters 8.1 and 8.2, respectively. In both chapters, the same drilling parameters (from Larsen's experiment) were used, and all variable drilling parameters for both models were equal. It is important to emphasize that the chosen values of the varying parameter differs from the values used by Larsen's, while the rest of the data set is kept constant during the modeling.

Models were compared using the following drilling parameters: mud weight, ROP, cuttings size, mud rheology, and drill-pipe diameter. Inclination angle of 75° degrees was chosen as the angle for flow velocity readings for each graph. In addition, the error equation (9.1)[5] was used in order to identify the distinctions or similarities between Larsen's and Rubiandini's models:

$$\boldsymbol{ERROR} = \left|\frac{V_{min,R.R} - V_{min,other}}{V_{min,R.R}}\right| * \mathbf{100\%} \quad \text{...} (9.1)$$

Mud Weight as a varying parameter

Flow velocity values were read off both for Larsen's model (figure 8.1.1) and for Rubiandini's model (figure 8.2.1). The flow velocity readings at 75° degrees are presented in table (9.1.1). From the table (9.1.1), both models indicate that flow velocity decreases at increasing mud weight values.

Mud weight value	**10 ppg**	**15 ppg**	**20 ppg**
Larsen's flow velocity (ft/sec) at 75° degrees	4,8	4,3	3,7
Rubiandini's flow velocity (ft/sec) at 75° degrees	5,76	5	3,51
Error	16 %	14 %	5 %

Table (9.1.1): Flow velocity value (ft/sec) versus angle of inclination, with mud weight as variable parameter.

As seen from table (9.1.1), flow velocities with three different mud weight values were compared. Readings of Larsen's flow velocity with mud weight equal to 10 and 15 ppg show a small disagreement with Rubiandini's flow velocity with the same mud weight values, having error value of 16 % and 14%, respectively. For mud weight equal to 20 ppg, the difference between these two models is very modest.

ROP as varying parameter

In table (9.1.2), Larsen's and Rubiandini's flow velocities with ROP as a varying parameter are presented. The common observation for graphs (8.1.2) and (8.2.2) is that ROP increases at increasing flow velocity rate. The results from the table seem reasonable since cuttings production increases when drilling with higher ROP. Hence, higher flow velocity rate is required in order to perform effective hole cleaning.

ROP	**30(ft/hr)**	**60(ft/hr)**	**120(ft/hr)**
Larsen's flow velocity (ft/sec) at 75° degrees	4,8	5,1	5,4
Rubiandini's flow velocity (ft/sec) at 75° degrees	5,5	6,1	6,5
Error	13 %	16 %	17%

Table (9.1.2): Flow velocity values versus angle of inclination with ROP as variable parameter.

Comparison of the Larsen's and Rubiandini's models indicate that error should be equal for all three given ROP values since cuttings velocity (V_{cut}) equation, in both models, is similar (that outlined by Larsen^2). By analyzing flow velocity readings of the two models, the error value appears to be slightly different for all three ROP values. The observed error difference could be due to readings uncertainty.

Cuttings size as variable parameter

It is a general statement that small cuttings are more difficult to transport since a higher flow velocity is required to transport them up to the surface. This phenomena presented by Larsen's model in figure (8.1.3) proves this statement. However, figure (8.2.3) (Rubiandini's model) illustrates that all three curves, having different cuttings size values, overlap each other. Hence, it is an indication that Rubiandini's model is not sensitive for small cuttings size predictions. However, it was still necessary to find out the effect of cuttings size variation on cuttings transport by using the Rubiandini's model. Therefore, in the graph (8.2.4), cuttings with larger difference in size, namely 0,09 inch, 0,9 inch, and 1 inch were chosen for modeling. The curves from figure (8.2.4) indicate the opposite trend when compared to figure (8.1.3), namely that large-sized cuttings are more difficult to bring up to the surface. For this reason, comparison of these two models when cuttings size is a varying parameter has no point.

By analyzing Rubiandini's model (chapter 6.2), it is clear that Rubiandini's model is based on Moore's vertical model and his slip velocity (V_{slip}). In return, Moore's model has a slip velocity that increases for increasing cuttings size, and this is reflected in Rubiandini's model.

Mud viscosity as varying parameter

After comparing Larsen's model (figure 8.1.4) with Rubiandini's model (figure 8.2.5) at 75° degrees of inclination, the differences in the flow velocity when mud rheology is varying are illustrated in table (9.1.3).

Mud Rheology	**PV=YP= 10**	**PV=YP= 15**	**PV=YP= 20**
Larsen's flow velocity (ft/sec) at 75° degrees	5,5	6,5	7,48
Rubiandini's flow velocity (ft/sec) at 75° degrees	6,4	6,9	7,25
Error	14 %	6 %	3 %

Table (9.1.3): Flow velocity values with mud viscosity as variable parameter.

As shows in the table (9.1.3), the difference between flow velocity in the Larsen's and Rubiandini's models are small. The differences between these two models decrease as mud rheology increases.

Drill-pipe diameter as variable parameter

By comparing Larsen's model (figure 8.1.5) with Rubiandini's model (figure 8.2.7) at 75° degrees of inclination, table (9.1.4) shows that flow velocity values vary insignificantly for both models. The error is almost equal for all three drill-pipe diameters, and the difference is possibly due to uncertainty in graph readings. In general, both Larsen's and Rubiandini's model should give the same error for all three different drill-pipe diameters. Because for both models, equations for cuttings velocity (V_{cut}) and for apparent viscosity that contain drill-pipe diameter are equal.

Drill Pipe Diameter	**2,375"in**	**2,9"in**	**3,4"in**
Larsen's flow velocity (ft/sec) at 75° degrees	5,1	5,25	5,6
Rubiandini's flow velocity (ft/sec) at 75° degrees	6	6,25	6,7
Error	15 %	16 %	16 %

Table (9.1.4): Flow velocity values versus angle with drill pipe diameter as a variable parameter.

As it was pointed out earlier, Larsen did not consider drill-pipe variation in his experimental work. Since Rubiandini based his model on the Larsen's work, drill-pipe variations were not considered by Rubiandini either. From table (9.1.4) it is observed that for smaller annulus (larger drill-pipe), the required flow velocity is higher.

9.2 Comparison of Larsen's and Rubiandini's models by using practical drilling situation

As described in chapter (8. 3), a wellbore with 4 drilling parameters that were close to reality was chosen. These drillings parameters were ROP, mud weight, cuttings size, and mud rheology. For Larsen's model, three different key inclination angles, namely 55°, 75°, and 90° degrees were selected for comparing required flow velocity and flow rate. For Rubiandini's model, two different well sections were selected, namely vertical section with 0° degrees of inclination (corresponds to Moore's vertical model), and horizontal well section with inclination angle from 45° to 90° degrees. The results from both models were compared with typical flow rate values (1500-2000 l/min) that are observed in an 8 ½" well section.

By analyzing flow rate results from the Larsen's model, the following observations were registered:

- For low ROP (10 m/hrs) (table 8.3.1.1), the flow rate values are within the range of typical flow rate values (1500- 2000 l/min). For higher ROP (30 and 50 m/hrs), the flow rate values are slightly above the typical flow rate range, approximately 100-200 (l/min) above the typical flow rate range.

- For all mud weight values (table 8.3.1.2), the flow rate values correspond to the typical range (1500-2000 l/min).
- For cuttings size (table 8.3.1.3), the flow rate values are almost in the range of typical flow rate values. The deviation from the range is minimal.
- For low mud rheology values (PV=YP= 7), the flow rate values are in the range of typical flow rate values. However, as mud rheology increases up to 15 PV and YP, the flow rate values keeps increasing and the difference is approximately 100 to 450 (l/min) above the typical flow rate range (table 8.3.1.4).

By interpreting flow rate values received from Rubiandini's model, the following observations are made:

- In the vertical section, flow rate values for low ROP (10 m/hrs) are located inside the typical flow rate range, while higher ROP values generate higher flow rate values that are greater than the typical range. In the horizontal well section, flow rate values vary between 2500 and 3100 (l/min) for low to high ROP, respectively. The difference between the observed flow rates and the typical range is as high as 1000 (l/min), which is a significant difference (table 8.3.2.1).
- In the vertical section, flow rate values for mud weight as variable are observed to be within the typical range. In the horizontal section, the flow rate values are above the typical range and the difference with typical range is between 200 and 500 (l/min) (table 8.3.2.2).
- In the vertical section, flow rate values for mud rheology as a variable correspond to the typical range. In the horizontal section, the flow rate values are above the typical range and the difference is between 500 and 1000 (l/min) (table 8.3.2.3).

From earlier observations in chapter (8. 2) where the cuttings size as a varying parameter was discussed, it was stated that Rubiandini's model predicted the opposite trend compared to the Larsen's model, namely that larger cuttings were difficult to transport. Therefore, comparison of these two models was excluded.

Based on analysis and observations listed above, the general trends for flow rate values can be indicated:

- Rubiandini's model for vertical well section gives flow rate that corresponds to the typical range in most cases. The existing inconsistency between the typical range and calculated flow rate values is insignificant.
- Rubiandini's model for horizontal section generates flow rates that are considerable above the typical range. The model seems to predict for high rates.

Larsen's model generates flow model that is in the typical range, in general. The inconsistency between the typical range and calculated flow rate values, based on drilling data from the example well, was observed in cases of high ROP values, small cuttings size, and high mud rheology values.

9. 3 Advantages and disadvantages of Larsen's and Rubiandini's models

The advantage of using Larsen's model is the ability to predict the transport flow velocity that is required for cuttings transport at different inclination angles. Especially, this method is advantageous when it shows a higher flow velocity in the interval between 65° and 75° degrees. Larsen developed correction factors for angle of inclination, cuttings size, and mud weight.

However, the Larsen's model is not applicable for the vertical wellbore, since the model was designed for high angle holes from 55° to 90° degrees. Another disadvantage of Larsen's model is that during the experiments, RPM was neglected and therefore, was not presented in the model. In addition, Larsen did not consider drill-pipe diameter as a varying parameters in his experiments and hence, could not establish whether drill-pipe diameter have any influence on the cuttings transport. However, well geometry was included in his model through the equation for cuttings velocity (V_{cut}). In this thesis, modeling on drill-pipe diameter as a variable was performed. It was observed that changes in diameter did affect the cuttings transport, namely that larger drill-pipe gave higher flow velocity. Finally, Larsen's experimental set up could be updated to a more realistic situation, namely more realistic pipe geometry, and the vibrations in the string should be added. In addition, cuttings, in his experiments, were injected in the system, which is not reflecting the real drilling situation, since it neglects pipe vibrations.

By using Rubiandini's model, it is possible to calculate the minimum flow velocity for both vertical and horizontal wellbore since the model was developed for inclination angles 0° to 90° degrees. The main advantage of Rubiandini's model compared to Larsen's model is that Rubiandini, in his research took RPM in to consideration. As it is shown in figure (8.2.6), at high RPM value, flow velocity decreases and therefore improves cuttings transport.

In his research, Rubiandini modified the Moore's slip velocity that was applicable for vertical wellbore in such way so that it would be possible to use in the inclined-until-horizontal wells. Rubiandini introduced slip velocity and correction factor for mud weight and angle of inclination. This was done by regression analysis using data from the Larsen's model and experimental data from both Larsen's and Peden's studies.

The graphs that are presented in chapter (8.2) have shown that flow velocity is constant at inclination angle between 45° and 90° degrees. This is not quite logical since flow velocity is hardly constant for such large angle interval.

By analyzing equation (6.1.6), it is obvious that minimum flow velocity (V_{min}) is dependent on inclination angle (θ), for angle of inclination less than 45°degrees. However, minimum flow velocity (V_{min}) in equation (6.1.7) is independent of inclination angle (θ) and therefore, V_{min} is constant for inclination angle larger than 45° degrees. For the vertical case Rubiandini's model is equal to Moore's model.
The modeling in this thesis revealed that Rubiandini's model is not sensitive for small-sized cuttings. In addition, predictions from Rubiandini's model contradict observations from

Larsen’s model, namely that larger cuttings are more difficult to transport. The modeling in this thesis revealed that larger drill pipe required larger flow velocity for cuttings transport.

9.4 Mechanistic model

In chapter 7, an introduction of a mechanistic two-layer model was presented. In chapter 7.1, Kamp’s model was explained in some details and mass conservation and momentum equations were introduced. In chapter 7.2, Gavignet’s two-layer model was presented in order to give a better explanation of the mechanistic model. In order to solve Kamp’s two-layer model numerically, the possible mathematical transformation was presented in chapter 7.3.

By analyzing chapter 7, it can be concluded that mechanistic model is quite complicated model that is dependent on several physical parameters, and closure laws are difficult to obtain. The results from Kamp’s model were compared with correlation-based model that was derived by Larsen. According to Kamp[4], predictions from Larsen model for mud flow rate were ten times as high as Kamp’s predictions indicating that there was still lacking good closure models to achieve realistic results with this mechanistic model.

9.5 Practical observations from field experience

During work experience offshore, the author has observed that shape of cuttings is mostly dependent on the formation type. Cuttings that come from hard formations, like limestone or claystone, usually have large size. Cuttings that are drilled from soft formations as sandstone or siltstone have more rounded shape, and are mostly dissolved in the mud during circulation.

It was also observed that larger cuttings have a larger surface area, so that they are easier to transport to the surface compared to smaller cuttings.

It is always a challenge for field geologist or paleontologist to define correct formation type in order to make the right decision during drilling. To define the formation type, the geologist is relaying on lag depth (depth cuttings were drilled at) and lag time (the time it takes for cuttings to arrive to the surface) parameter that is monitored by data operator on board. However, the lag depth is not always the correct parameter since lag depth itself depends on several other parameters. An addition, the hole diameter varies through the depth due to various drillings situations (collapse, tight hole, fracturing) and that affect the lag depth measurements.

During drilling operation, the author has noticed that larger cuttings are brought to surface faster than the smaller ones. Also, after drilling operation is finished, the hole is being circulated several times to make sure that hole is properly cleaned (the bottom-up procedure). Here, it was discovered that cutting size get smaller and smaller compared to cuttings that were observed under drilling. Therefore, author believes that for better monitoring of hole cleaning process, it is necessary to have two lag depth measurements; one for larger cuttings and one for smaller ones, since larger cuttings are brought to surface faster than smaller ones.

To sum up, parameters that affect cuttings transport in the annulus can be divided into three different groups. The first group consists of fluid parameters that include fluid viscosity, fluid density, and fluid flow rate. The second group consists of cuttings parameters like cuttings density, cuttings shape and size, and cuttings concentration in the annulus. The third group consists of drill-pipe parameters, such as drill-pipe diameter, drill-pipe rotation (RPM) and drill-pipe eccentricity and drill-pipe inclination.

Figure (9.5.1) illustrates a hole-cleanings chart that is used today on the well side. The section was drilled from 1270 m to 3124 m MD. The data operator uses this chart on the field to control the hole cleaning process. This chart is built in an Excel spreadsheet (Appendix F).

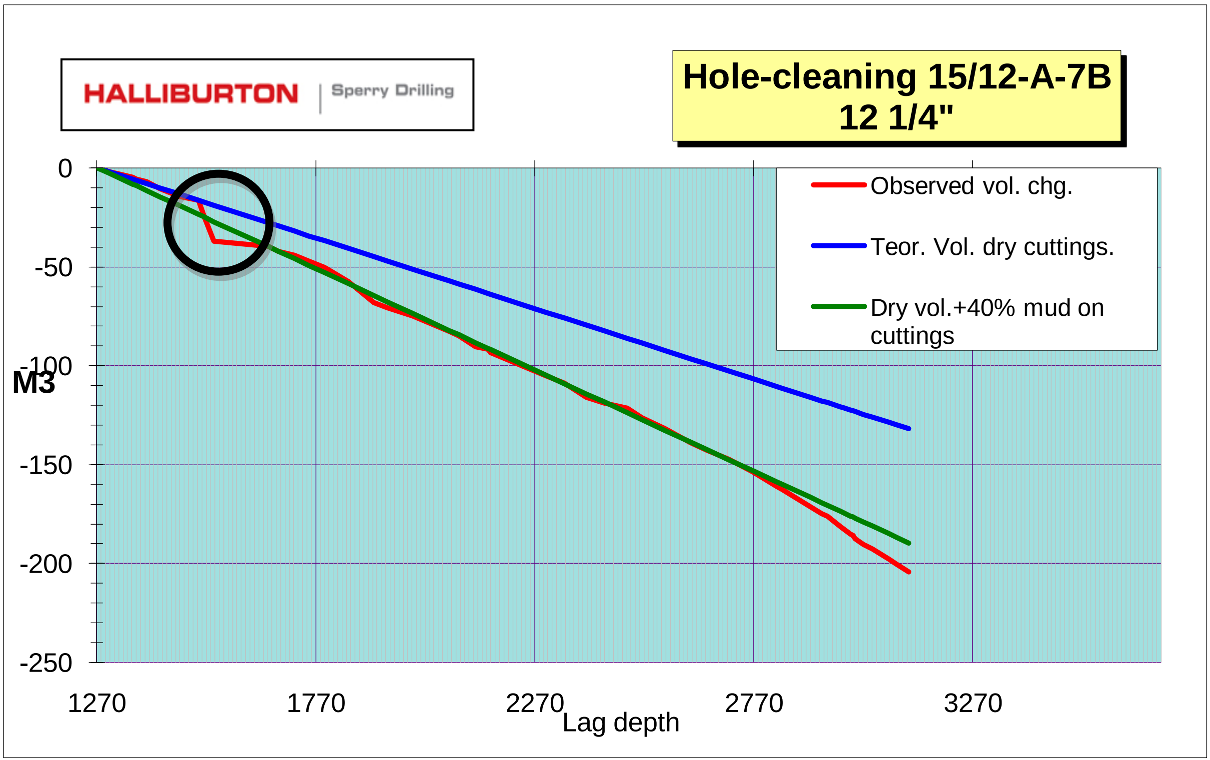


Figure (9.5.1): Hole cleaning chart representing lag depth vs. drilled volume.
From Maersk Guardian rig.

The chart usually consists of two linear lines; one blue line on top, and one green line on the bottom. The blue line represents the expected value of dry cuttings volume, and the green line corresponds to the expected volume of wetted cuttings that were brought to the surface. The red line represents the observed cuttings volume change. If the red line lies between the blue and green lines, then we have an acceptable hole cleaning. When the red line lies close to the blue line or above it, it indicates cuttings are accumulated in the wellbore and it is danger for stuck pipe. In case of red line lies under the green line, then it is a sign of mud and cuttings loss to the formation.

As we can see from figure (9.5.1), the red line is placed very tight to the green line, meaning that cuttings are covered with mud, "wet cuttings". It is also a sign of good hole cleaning. However, the black circle on the chart indicates the loss of mud to formation since the red line shows a peck that is below the green line.

10. CONCLUSION

Studies on cuttings transport and hole cleaning in inclined and horizontal wellbore was initiated in the early 1980's. The majority of scientists, in their research, focused on drillings parameters, mud rheological factors, and other variables that could influence cuttings transport. Most of the studies were performed by using the empirical approach, where empirical models were developed based on an extensive experimental work. Another group of scientists applied the mechanistic approach i.e. solved a set of equations numerically, in order to develop different numerical simulation models for cuttings transport. In recent years, only few studies on cuttings transport on hole cleaning in inclined wellbore were performed.
In this thesis, the author presented both approaches; the detailed analysis of three empirically developed models, namely Peden's[1], Larsen's[2], and Rubiandini's[5] models and two numerical models developed by Kamp and Rivero[4] and Gavignet and Sobey[3] using the mechanistic approach. These two models were introduced in order to illustrate the complexity of this modeling.

In addition, the thesis demonstrates how Kamp's two-layer model has to be reformulated mathematically before a numerical method can be used for solving the model, since Kamp and Rivero, in their publication, did not show this in details.

The analysis shows that mechanistic model is quite complicated model that is dependent on several physical parameters. Even if they are complicated, they do not necessarily provide with realistic results. In contrary, the empirical models give more realistic flow rate predictions that are close to realistic drilling conditions. However, some improvements can be applied to empirical model, for instance Larsen's model, in order to correspond to more realistic drilling situation.

Application of Larsen's and Rubiandini's models was performed based on Larsen's paper, in order to establish the differences between these two models and to observe how various drilling parameters affect cutting transport. The following conclusions were made from the simulation:

- *Mud weight as a variable:* both models showed the same trend, i.e. the flow velocity decreases as mud weight increases. This means that high mud weight improves cuttings transport. The difference between the two models decreases as mud weight increases.
- *ROP as a variable:* both models showed the same pattern, namely high ROP values generate high flow velocity. The difference between these two models was rather small (13%, 16%, and 17%).
- *Cuttings size as a variable:* the models showed the opposite tendency, namely Larsen's model showed that smaller cuttings require high flow velocity in order to be transported. Hence, smaller cuttings are difficult to transport. From Rubiandini's model, it was seen that larger cuttings demanded higher flow velocity meaning that

larger cuttings was difficult to transport. Field experience seems to support that the trend Larsen predicts is correct.

- *Mud rheology as a variable:* both models indicated the same trend, namely higher mud rheology produced higher flow velocity. The difference between the two models decreases as mud rheological parameters are increased.
- *Drill-pipe diameter:* the similar tendency was registered for both models, namely flow velocity increased as drill-pipe diameter increased. The difference between the models seemed to be insignificant (15%), and this sounds reasonable since well geometry is treated equally in the models.
- *RPM as a variable:* higher RPM values generate lower flow velocity. This parameter was modeled only for Rubiandini's model since Larsen's model neglected this parameter.

Moreover, Larsen's and Rubiandini's models were modeled using the example data from a practical drilling situation in order to determine the required flow rate and compare it to flow rate (1500-2000 l/min) that is typical for drilling the 8 ½" well section.

- *Mud weight as a variable:* flow rates generated by Larsen's model corresponded to typical range, while flow rates modeled by Rubiandini's model gave the following results: flow rates in vertical section (0° degrees of inclination) corresponded to typical flow range, while flow rates in horizontal section (45°-90° of inclination) were above the typical flow rate range.
- *ROP as a variable:* In the Larsen's model, flow rates for low ROP corresponded to typical range, while flow rates for high ROP were just outside the typical range with minimal difference.
  In Rubiandini's model, flow rates for low ROP in vertical section (0° degrees of inclination) corresponded to typical flow range and for high ROP, flow rates were above the typical range. On the other hand, flow rates in horizontal section (45°-90° of inclination) were above the typical flow rate range.
- *Cuttings size as a variable:* In the Larsen's model, flow rates for small cuttings size did not correspond to typical range, while flow rates for large cuttings corresponded to that range. The modeling proved the statement that smaller sized cuttings were difficult to transport since it required higher flow rate.
  On the other hand, the simulation for Rubiandini's model was not performed since the model was not suitable for small-sized cuttings transport predictions.
- *Mud rheology as a variable:* In the Larsen's model, flow rates for low mud rheology corresponded to typical range, while flow rates for high mud rheology were above the typical range.
  In the Rubiandini's model, flow rates in vertical section (0° degrees of inclination) corresponded to typical flow range; flow rates in horizontal section (45°-90° of inclination) were above the typical flow rate range with significant difference.

Based on all simulations that were performed using Larsen's and Rubiandini's models, it can be concluded that Rubiandini's required flow rate for cuttings transport over-predicts

Larsen's model in all situations. As it was observed by Kamp[4], the required flow rate for cuttings transport based on Kamp's model was ten times lower than flow rates predicted by Larsen's model. In addition, Larsen is known to have a reputation for over predicting mud flow rates observed in the field. This statement indicates that Rubiandini's model gives very high flow rate over-prediction.

Based on broad study of cuttings transport and field experiences, the following suggestions are recommended to achieve better hole cleaning and cuttings transport:

- Drill-pipe rotation can prevent cuttings beds build-up, and thus improve hole cleaning. Drill pipe rotation is effective on hole cleaning since it results in a turbulent flow in the annulus. The rotation of the drill pipe is more advantageous in viscous drilling fluid and in small wellbore. In cases, where drill pipe does not rotate, it is difficult to remove cuttings bed. In these situations, wiper trips are necessary to improve hole cleaning. Usually, a normal range of drill pipe rotation is around 90 to 180 rpm. The pipe can rotate up to 120-rpm when drill bit is on-bottom, and 180-rpm drill bit is off-bottom. In unstable formations, like sandstone, a high rpm values should be avoided, since the drill sting rotations can cause loss of some parts of wellbore formation (washouts). In addition, high rpm can cause high vibration in the drill string and thus, damage the electronics part in the BHA, like Geo-Pilot or the MWD tools.

- It is important to monitor the shakers before trip out (or pull out) in order to ensure that cuttings return rate has reduced. During drilling operation, it is common to circulate wellbore several times (the process is called circulate bottom-up) before starting tripping out of hole. The purpose is to avoid stuck of drill pipe during pull out and be able to reach the bottom hole with drill bit or casing, when we trip into the hole again. The common practice is to have at least three bottoms-up with slow pipe rotation before tripping out of the hole. If ECD measurement tool is available on the BHA, it has to be controlled that the ECD has dropped to normal level.

- During drilling, if transport of cuttings is a problem, the flow rate should be increased to its upper level, especially in the range of higher angles between 55° to 90° degrees. One has to be aware that inclinations between 40° to 45° degrees are critical since cuttings can slide down during e.g. connections when pumps are off.

- In the wellbore with inclination angle from 0° to 45° degrees, laminar flow in annulus and increasing yield value of mud to its limit is recommended. In the intermediate inclination from 45° to 55° degrees, it is possible to use either turbulent or laminar flow. In the high deviated wellbore with inclination angle from 55° to 90° degrees, a turbulent flow regime has a better effect on hole cleaning than laminar flow.

- Small cuttings create more packed cuttings bed. The height of cuttings bed is higher at inclination between 65° to 70° degrees, since hole cleaning is more difficult in this interval. In this case, a high rotary speed with a high viscosity mud would benefit to transport small-sized cuttings. When the drill pipe does not rotate, a low viscosity mud cleans the wellbore better than high viscosity mud.

- Field data indicate that the annular cuttings concentration is the main factor that causes pipe sticking, high torque, and drag. Annular cuttings concentration is the parameter that should be considered for the cuttings transport in directional well drilling. In case of highly inclined or tight well, it is important to ream the wellbore with help of a back reamer. It helps creating a bigger hole that can eliminate risk of stuck drill-pipe.

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Appendix A

In this appendix, MatLab codes that were used to draw various graphs that are presented in chapter 4 are displayed. In addition, data for drawing estimated cuttings concentration in annulus versus ROP is presented in table A.1.

MatLab code for estimated cuttings concentration in annulus versus ROP:

```
%Cuttings Concentration Versus Rate of Penetration at CTFV
ROP=(0:2:120);
Ccc=((0.01778*ROP)+0.505);
plot (ROP,Ccc)
title('Cuttings Concentration VS. ROP')
xlabel('ROP (ft/hrs)')
ylabel('Cuttings Concentration %')
axis ([0,120,0,3])
```

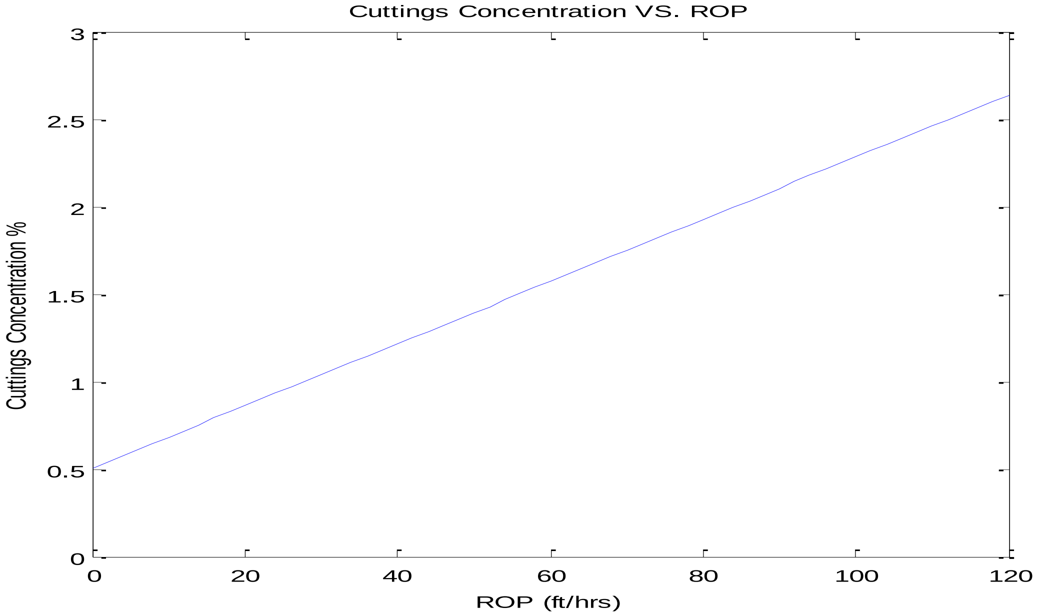

Figure (A.1): Cuttings concentration in annulus versus ROP.

MatLab code for correction factor for angle of inclination between 55°and 90° degrees:

```
%Correction factor for angle of Inclination
ang=(55:0.1:90);
w=(0.0342*(ang));
l=(0.000233*(ang).^2);
Cang=(w-l-0.213)
plot(ang,Cang)
title('Correction Factor for Angle of Inclination VS. Angle')
xlabel('Angle')
ylabel('Correction Factor')
```

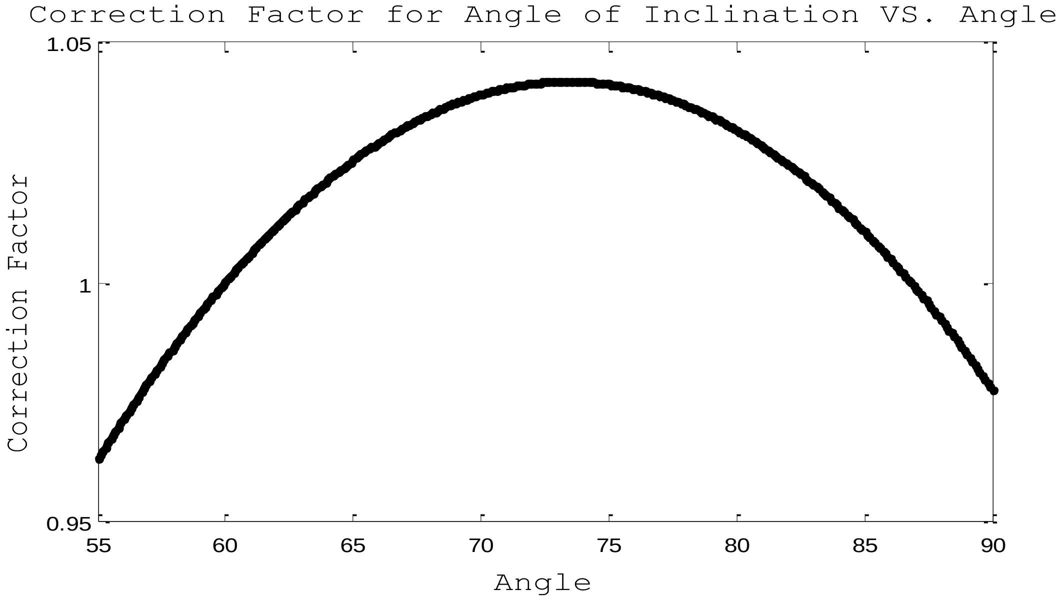

Figure (A.2): Correction factor for angle of inclination between 55°and 90° degrees.

MatLab code for cuttings size correlation factor versus cuttings size:

```
%correction factor for cuttings size
Dcutt=(0.06:0.01:0.5);
Csize=(-1.04*(Dcutt))+1.286;
plot(Dcutt,Csize)
title('Cuttings Distribution')
xlabel('Average Cuttings Size (inch)')
ylabel('Cuttings Correction Factor')
```

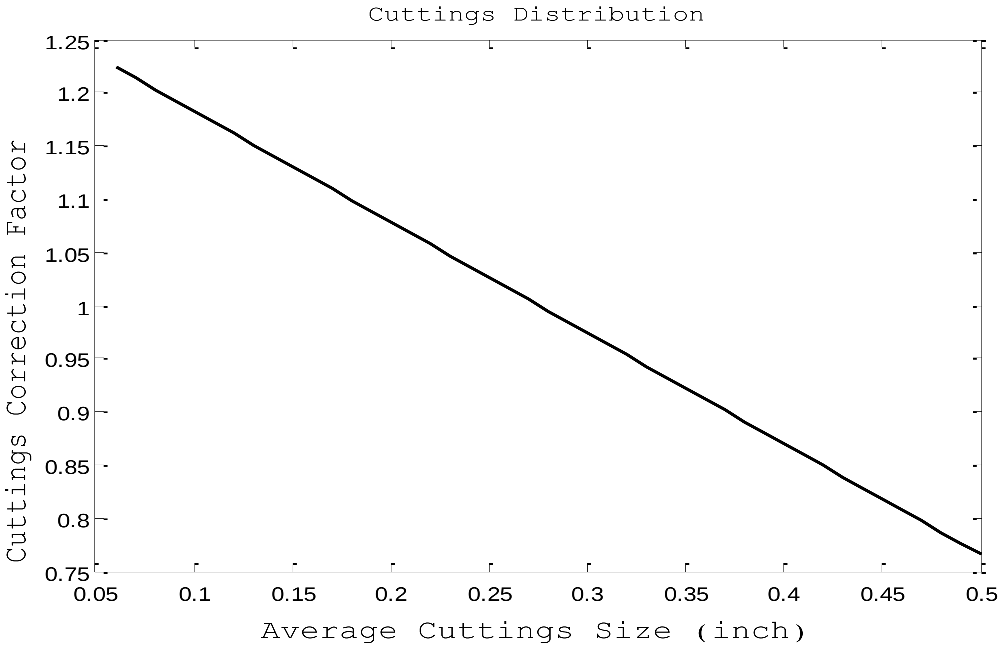

Figure (A.3): Cuttings size correlation factor versus cuttings size.

MatLab code for correction factor of mud weight versus mud weight (ppg):

```
%Correction factor for mud weight
% pm= mud dencity
pm =(8.57:20);
if (pm>=8.57);
Cmwt=(1-0.0333*(pm-8.7));
else
    Cmwt=1;
end
%Vslip=(vs2*Cang*Csize*Cmwt);
plot(pm,Cmwt)
%axis ([8,17,0.7,1.5])
title('Correction Factor for Mud Weight ')
xlabel('Mud Weight (ppg)')
ylabel('Correction Factor')
```

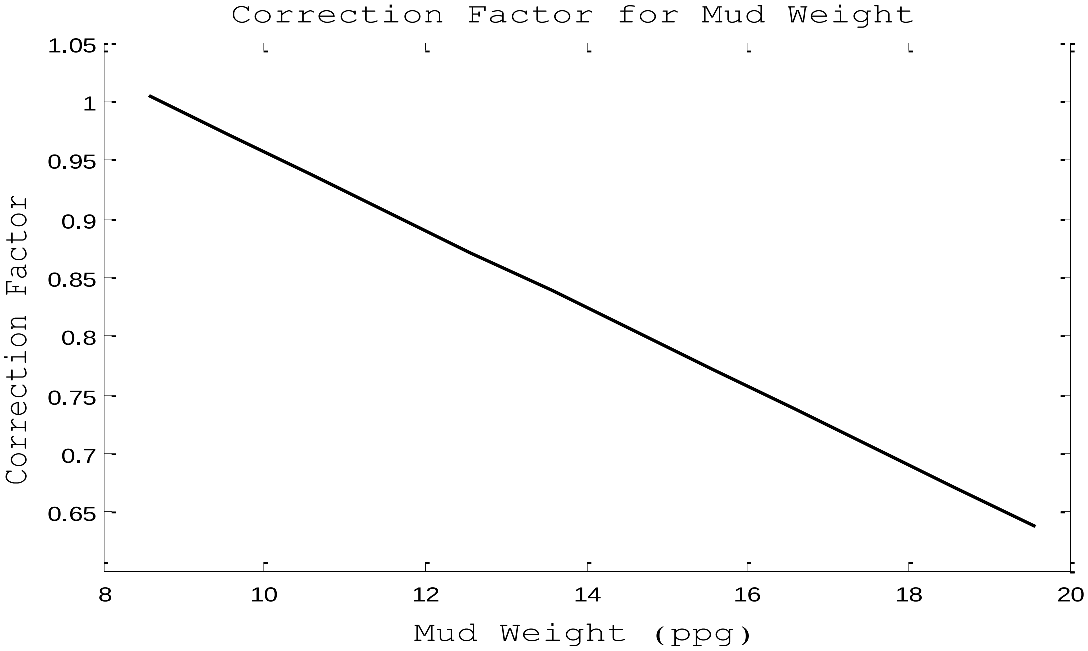

Figure (A.4): Correction factor of mud weight versus mud weight (ppg).

MatLab code for correction factor for cuttings concentration at sub-critical fluid:

```
%Correction factor for cutting concentration
%at sub critical fluid flow
u=(0:120);
Cb=0.97-(0.00231*u);
plot(u,Cb)
title('SCFF Correction Factor')
xlabel('Apparent Viscosity (CP)')
ylabel('Correction Factor')
```

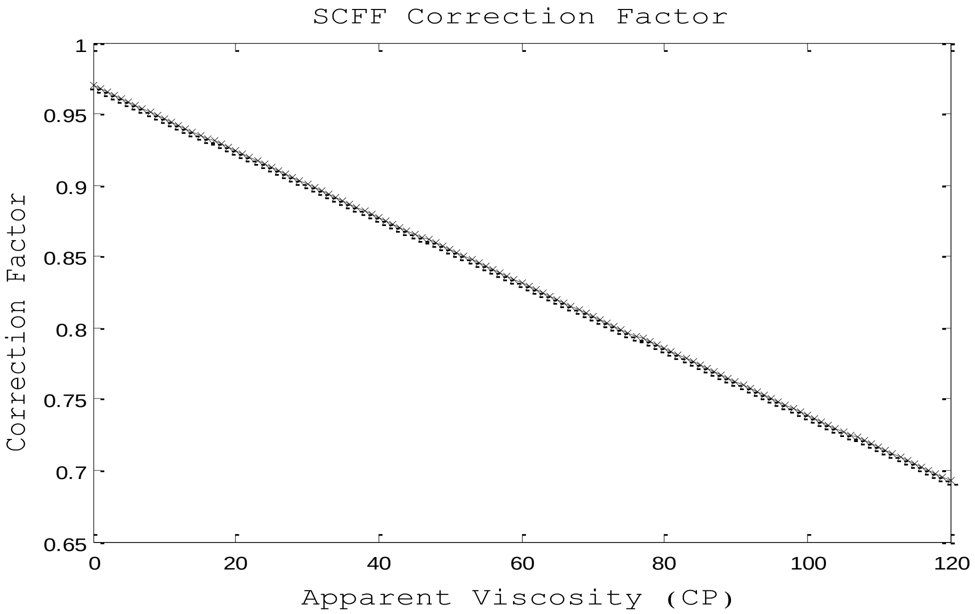

Figure (A.5): Correction factor for cuttings concentration at sub-critical fluid flow.

Appendix B

In this appendix, MatLab codes that were used to draw various graphs for application of Larsen's model that are presented in chapter 8.1 are displayed.

MatLab code for flow velocity vs. angle with mud weight as a variable:

```
%Cuttings viscosity
Dpipe=2.375;
Dhole=5;
ROP=54;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
b=0.64+(18.16/ROP);
vcut=1/(a*b);
%Assume vs1
vs1=1;
vs2=vs1;
n=0
while (vs2-vs1)<=0.01
Vcrit=vs1+vcut;
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=7;
YP=7;
C1=5*YP*D1/Vcrit;
u=PV+C1;
% calculate vs2
if (u<53)
vs2=(0.00516*u)+3.006;
else
 vs2=0.02554*(u-53)+3.28;
end
n=n+1
end
%Correction factor for angle
ang=(55:1:90);
w=(0.0342*(ang));
L=(0.000233*(ang.^2));
Cang=(w-L-0.213);
%correction factor for cuttings size
Dcutt=0.175;
Csize=-1.04*(Dcutt)+1.286;
%Correction factor for mud weight
% pm= mud weight (ppg)
pm =20;
if (pm>=8.57);
Cmwt=(1-0.0333*(pm-8.7));
else
    Cmwt=1;
end
Vslip=(vs2*Cang*Csize*Cmwt);
%plot(ang,vslip)
Vmin=Vslip+vcut
plot(ang,Vmin,ang,a1,ang,a2)
title('Velocity vs. Angle with Mud Weight as a variable')
xlabel('Angle (deg)')
ylabel('Velocity (ft/sec)')
axis ([55,90,3,6])
```

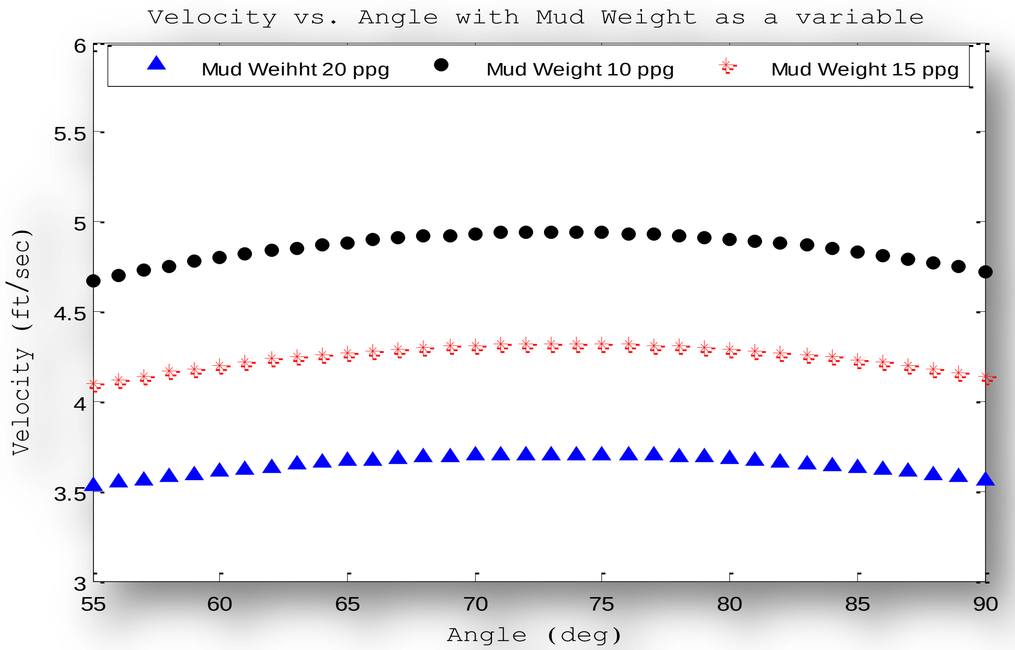

Figure (B.1): Flow velocity vs. Angle when the mud weight is a variable parameter.

MatLab code for flow velocity vs. angle of inclination with variation of ROP (ft/hr):

```
%Cuttings viscosity
Dpipe=2.375;
Dhole=5;
ROP=120;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
b=0.64+(18.16/ROP);
vcut=1/(a*b);
%Assume vs1
vs1=1;
vs2=vs1;
n=0
while (vs2-vs1)<=0.01
Vcrit=vs1+vcut;
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=7;
YP=7;
C1=5*YP*D1/Vcrit;
u=PV+C1;
% calculate vs2
if (u<53)
vs2=(0.00516*u)+3.006;
else
 vs2=0.02554*(u-53)+3.28;
end
n=n+1
end
%Correction factor for angle
ang=(55:1:90);
```

```
w=(0.0342*(ang));
L=(0.000233*(ang.^2));
Cang=(w-L-0.213);
%correction factor for cuttings size
Dcutt=0.175;
Csize=-1.04*(Dcutt)+1.286;
%Correction factor for mud weight
% pm= mud weight (ppg)
pm=8.57;
if (pm>=8.57);
Cmwt=(1-0.0333*(pm-8.7));
else
    Cmwt=1;
end
Vslip=(vs2*Cang*Csize*Cmwt);
%plot(ang,vslip)
Vmin=Vslip+vcut
plot(ang,Vmin,ang,a1,ang,a2)
title('Velocity vs. Angle with ROP as a variable')
xlabel('Angle (deg)')
ylabel('Velocity (ft/sec)')
axis ([55,90,3,6])
```

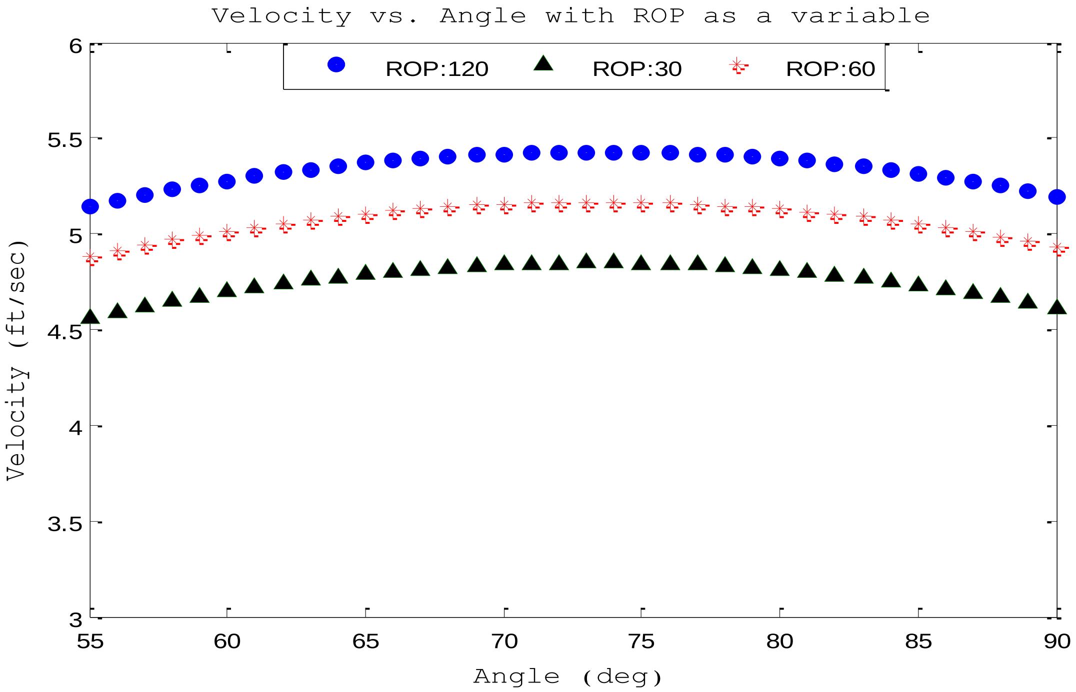

Figure (B.2): Flow velocity vs. angle of inclination with variation of ROP (ft/hr).

MatLab code for flow velocity vs. angle of inclination with variation of cuttings size:

```
%Cuttings viscosity
Dpipe=2.375;
Dhole=5;
ROP=54;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
b=0.64+(18.16/ROP);
vcut=1/(a*b);
```

```
%Assume vs1
vs1=1;
vs2=vs1;
n=0
while (vs2-vs1)<=0.01
Vcrit=vs1+vcut;
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=7;
YP=7;
C1=5*YP*D1/Vcrit;
u=PV+C1;
% calculate vs2
if (u<53)
vs2=(0.00516*u)+3.006;
else
 vs2=0.02554*(u-53)+3.28;
end
n=n+1
end
%Correction factor for angle
ang=(55:1:90);
w=(0.0342*(ang));
L=(0.000233*(ang.^2));
Cang=(w-L-0.213);
%correction factor for cuttings size
Dcutt=0.6;
Csize=-1.04*(Dcutt)+1.286;
%Correction factor for mud weight
% pm= mud weight (ppg)
pm=8.57;
if (pm>=8.57);
Cmwt=(1-0.0333*(pm-8.7));
else
    Cmwt=1;
end
Vslip=(vs2*Cang*Csize*Cmwt);
%plot(ang,vslip)
Vmin=Vslip+vcut
plot(ang,Vmin,ang,a1,ang,a2)
title('Velocity vs. Angle with Cuttings Size as a variable')
xlabel('Angle (deg)')
ylabel('Velocity (ft/sec)')
axis ([55,90,3,6])
```

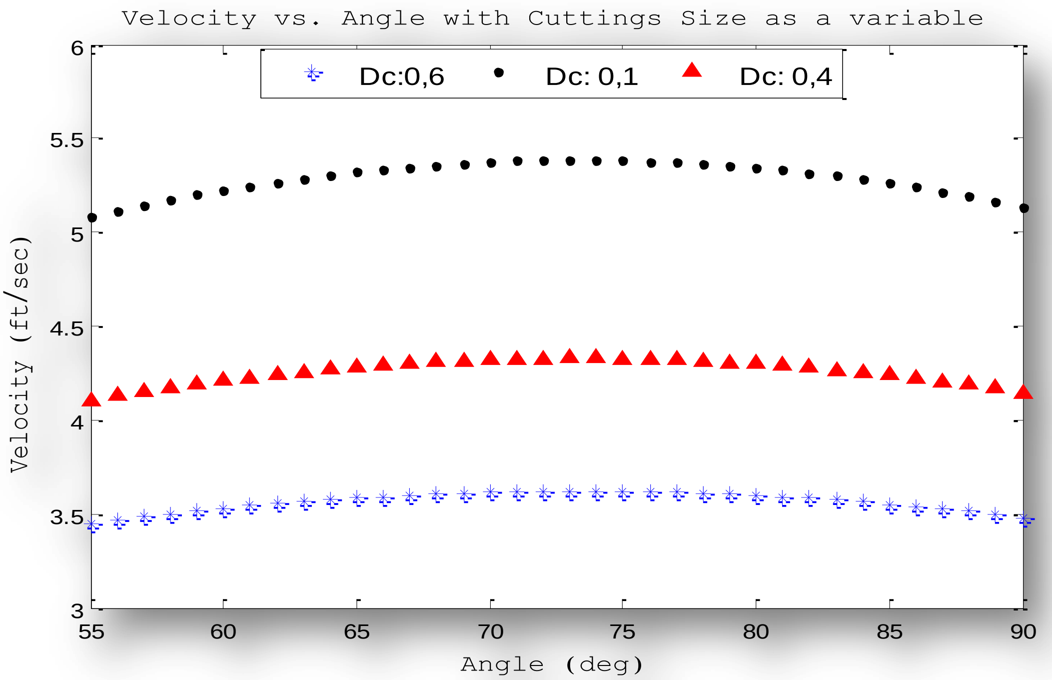

Figure (B.3): Flow velocity vs. angle of inclination with variation of cuttings size (inch).

MatLab code for Flow velocity vs. angle of inclination with mud rheology as variable:

```
%Cuttings viscosity
Dpipe=2.375;
Dhole=5;
ROP=54;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
b=0.64+(18.16/ROP);
vcut=1/(a*b);
%Assume vs1
vs1=1;
vs2=vs1
n=0
while (vs2-vs1)<=0.01
Vcrit=vs1+vcut;
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=20;
YP=20;
C1=5*YP*D1/Vcrit;
u=PV+C1;
% calculate vs2
if (u<53)
vs2=(0.00516*u)+3.006;
else
 vs2=0.02554*(u-53)+3.28;
end
n=n+1
end
%Correction factor for angle
ang=(55:1:90);
w=(0.0342*(ang));
L=(0.000233*(ang.^2));
```

```
Cang=(w-L-0.213);
%correction factor for cuttings size
Dcutt=0.175;
Csize=-1.04*(Dcutt)+1.286;
%Correction factor for mud weight
% pm= mud weight (ppg)
pm=8.57;
if (pm>=8.57);
Cmwt=(1-0.0333*(pm-8.7));
else
    Cmwt=1;
end
Vslip=(vs2*Cang*Csize*Cmwt);
%plot(ang,vslip)
Vmin= (Vslip+vcut)
plot(ang,Vmin,ang,a1,ang,a2)
title('Velocity vs. Angle with Mud Rheology as a variable')
xlabel('Angle (deg)')
ylabel('Velocity (ft/sec)')
axis ([55,90,4,8])
```

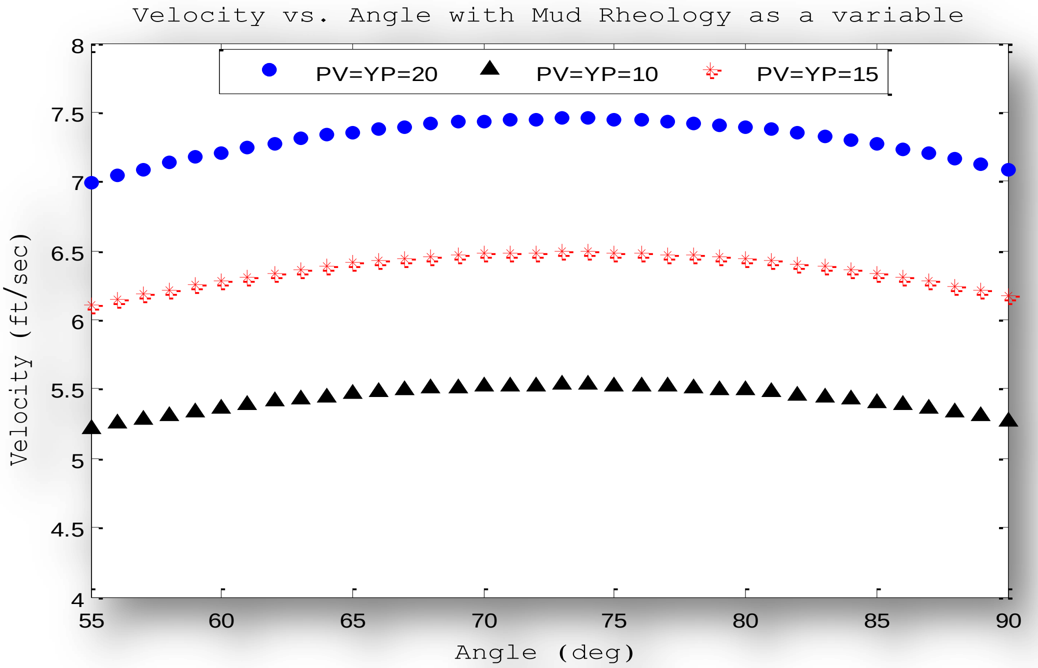

Figure (B.4): Flow velocity vs. angle of inclination with mud rheology as variable.

MatLab code for flow velocity versus angle of inclination when the drill-pipe diameter: varies:

```
%Cuttings viscosity
Dpipe=2.375;
Dhole=5;
ROP=54;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
b=0.64+(18.16/ROP);
vcut=1/(a*b);
%Assume vs1
vs1=1;
vs2=vs1
```

```
n=0
while (vs2-vs1)<=0.01
Vcrit=vs1+vcut;
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=20;
YP=20;
C1=5*YP*D1/Vcrit;
u=PV+C1;
% calculate vs2
if (u<53)
vs2=(0.00516*u)+3.006;
else
 vs2=0.02554*(u-53)+3.28;
end
n=n+1
end
%Correction factor for angle
ang=(55:1:90);
w=(0.0342*(ang));
L=(0.000233*(ang.^2));
Cang=(w-L-0.213);
%correction factor for cuttings size
Dcutt=0.175;
Csize=-1.04*(Dcutt)+1.286;
%Correction factor for mud weight
% pm= mud weight (ppg)
pm=8.57;
if (pm>=8.57);
Cmwt=(1-0.0333*(pm-8.7));
else
    Cmwt=1;
end
Vslip=(vs2*Cang*Csize*Cmwt);
%plot(ang,vslip)
Vmin= (Vslip+vcut)
plot(ang,Vmin,ang,a1,ang,a2)
title('Velocity vs. Angle with Drill-Pipe Diameter as a variable')
xlabel('Angle (deg)')
ylabel('Velocity (ft/sec)')
axis ([55,90,4,8])
```

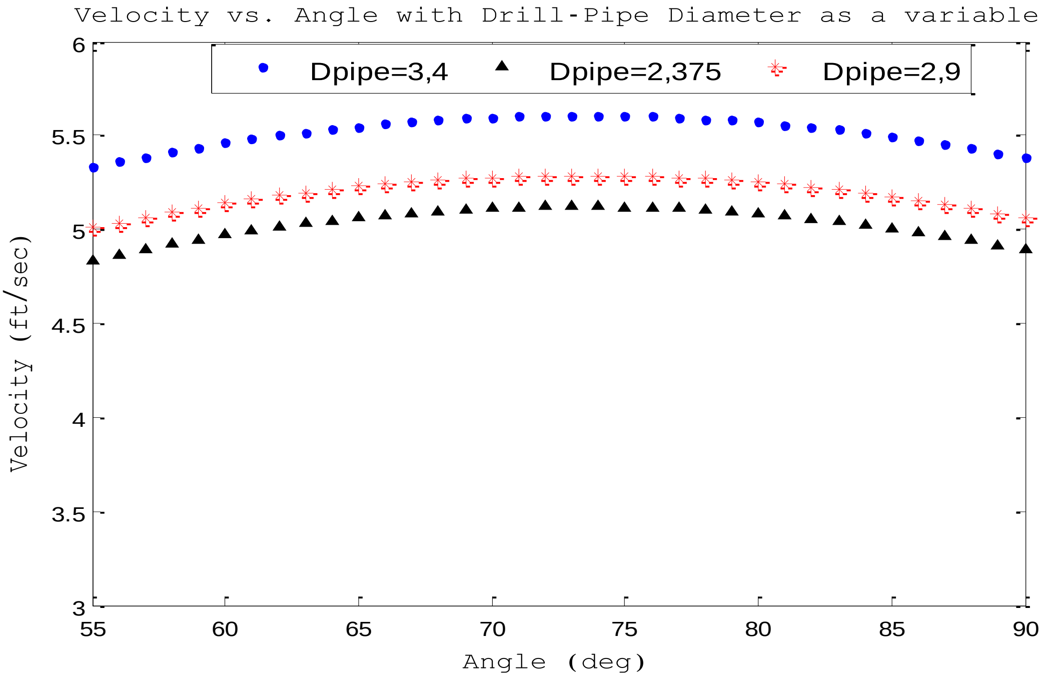

Figure (B.5): Flow velocity vs. angle of inclination when the drill-pipe diameter varies.

Appendix C

In this appendix, MatLab codes that were used to draw various graphs for application of Rubiandini's model that are presented in chapter 8.2 are displayed.

MatLab code for flow velocity vs. angle of inclination when the mud weight varies:

```
%Cuttings viscosity
Dpipe=2.375;
Dhole=5;
ROP=54;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
Cconc=(0.01778*ROP)+0.505;
vcut=(ROP/(36*a*Cconc));
vs1=0.1;
n=0
vsv=0.2;
while (abs(vsv-vs1)>0.001)
n=n+1
Vmin=vcut+vs1;
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=7;
YP=7;
C1=(5*YP*D1)/vmin;
u=PV+C1;
Dcut=0.175;
Pm=20;
Re= (928*Pm*Dcut*vs1)/u;
% calculate vs2
if (Re<3)
    f=40/Re;
elseif ((Re>3)&(Re<300))
 f=22/sqrt(Re);
else
    f=1.54;
end
Ps=19;
vsv=f*(sqrt(Dcut*((Ps-Pm)/Pm)))
vs1=((vsv+vs1)/2);
end
%end of while
RPM= 80;
for i= (1:90)
    ang(i)=i;
if (ang(i) <= 45)
     vs = vcut+(1+ (ang(i)*(600-RPM)*(3+Pm)/202500))*vsv;
else
    vs= vcut+((1+(3+Pm)*(600-RPM)/4500))*vsv;
end
    Vmin(i)= vcut+vs
end
plot(ang,Vmin,ang,a1,ang,a2)
title('Velocity vs. Angle with Mud Weight as variable')
xlabel('Angle (deg)')
ylabel('Velocity (ft/sec)')
%axis ([0,90,2.5,9]
```

Figure (C.1): Minimum flow velocity vs. angle of inclination when the mud weight varies.

MatLab code for flow velocity vs. angle of inclination when ROP varies:

```
%%Cuttings viscosity
Dpipe=2.375;
Dhole=5;
ROP=120;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
Cconc=(0.01778*ROP)+0.505;
vcut=(ROP/(36*a*Cconc));
vs1=0.1;
n=0
vsv=0.2;
while (abs(vsv-vs1)>0.001)
n=n+1
Vmin=vcut+vs1;
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=7;
YP=7;
C1=(5*YP*D1)/vmin;
u=PV+C1;
Dcut=0.175;
Pm=8.57;
Re= (928*Pm*Dcut*vs1)/u;
% calculate vs2
if (Re<3)
    f=40/Re;
elseif ((Re>3)&(Re<300))
 f=22/sqrt(Re);
else
    f=1.54;
end
```

```
Ps=19;
vsv=f*(sqrt(Dcut*((Ps-Pm)/Pm)))
vs1=((vsv+vs1)/2);
end
%end of while
RPM= 80;
for i= (1:90)
    ang(i)=i;
if (ang(i) <= 45)
    vs = vcut+(1+ (ang(i)*(600-RPM)*(3+Pm)/202500))*vsv;
else
    vs= vcut+((1+(3+Pm)*(600-RPM)/4500))*vsv;
end
    Vmin(i)= vcut+vs
end
plot(ang,Vmin,ang,a1,ang,a2)
title('Velocity vs. Angle with ROP as variable')
xlabel('Angle (deg)')
ylabel('Velocity (ft/sec)')
%axis ([0,90,2.5,9])
```

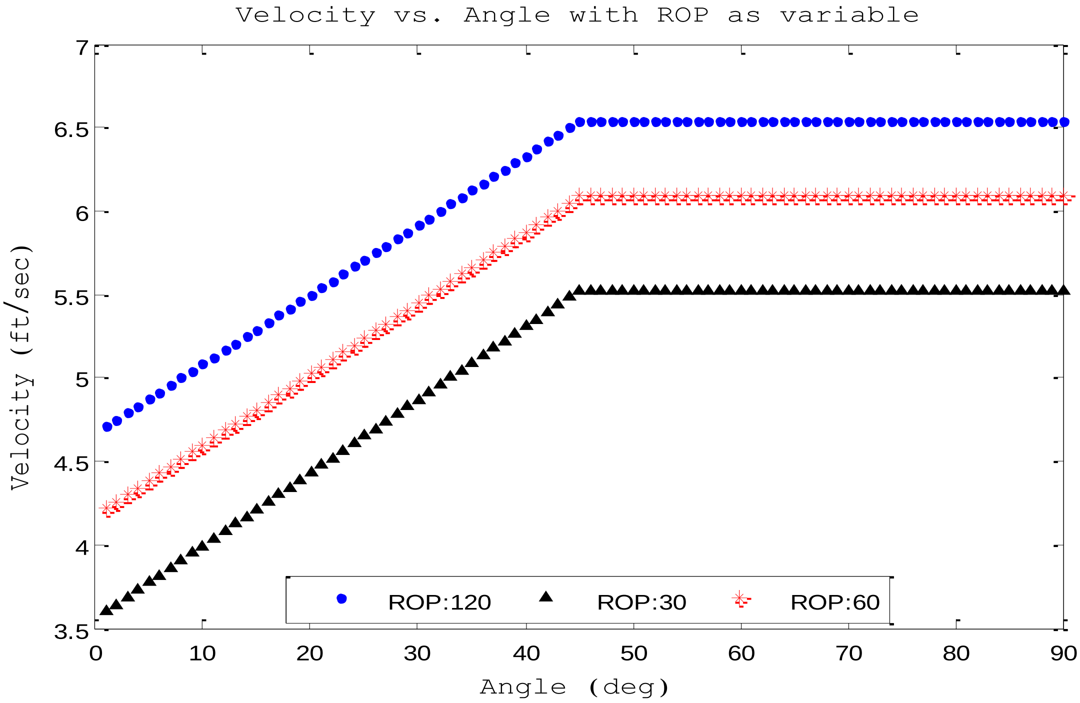

Figure (C.2): Minimum flow velocity versus angle of inclination when the ROP (ft/hr) varies.

MatLab code for flow velocity vs. angle of inclination when the cuttings size varies:

```
%Cuttings viscosity
Dpipe=2.375;
Dhole=5;
ROP=540;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
Cconc=(0.01778*ROP)+0.505;
vcut=(ROP/(36*a*Cconc));
vs1=0.1;
n=0
vsv=0.2;
```

```
while (abs(vsv-vs1)>0.001)
n=n+1
Vmin=vcut+vs1;
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=7;
YP=7;
C1=(5*YP*D1)/vmin;
u=PV+C1;
Dcut=0.175;
Pm=8.57;
Re= (928*Pm*Dcut*vs1)/u;
% calculate vs2
if (Re<3)
    f=40/Re;
elseif ((Re>3)&(Re<300))
 f=22/sqrt(Re);
else
    f=1.54;
end
Ps=19;
vsv=f*(sqrt(Dcut*((Ps-Pm)/Pm)))
vs1=((vsv+vs1)/2);
end
%end of while
RPM= 80;
for i= (1:90)
    ang(i)=i;
if (ang(i) <= 45)
    vs = vcut+(1+ (ang(i)*(600-RPM)*(3+Pm)/202500))*vsv;
else
    vs= vcut+((1+(3+Pm)*(600-RPM)/4500))*vsv;
end
    Vmin(i)= vcut+vs
end
plot(ang,Vmin)
title('Minimum Velocity VS. Angle when The Cuttings Size Varies')
xlabel('Angle')
ylabel('Minimum Velocity (Vmin)')
axis ([0,90,3.0,7])
```

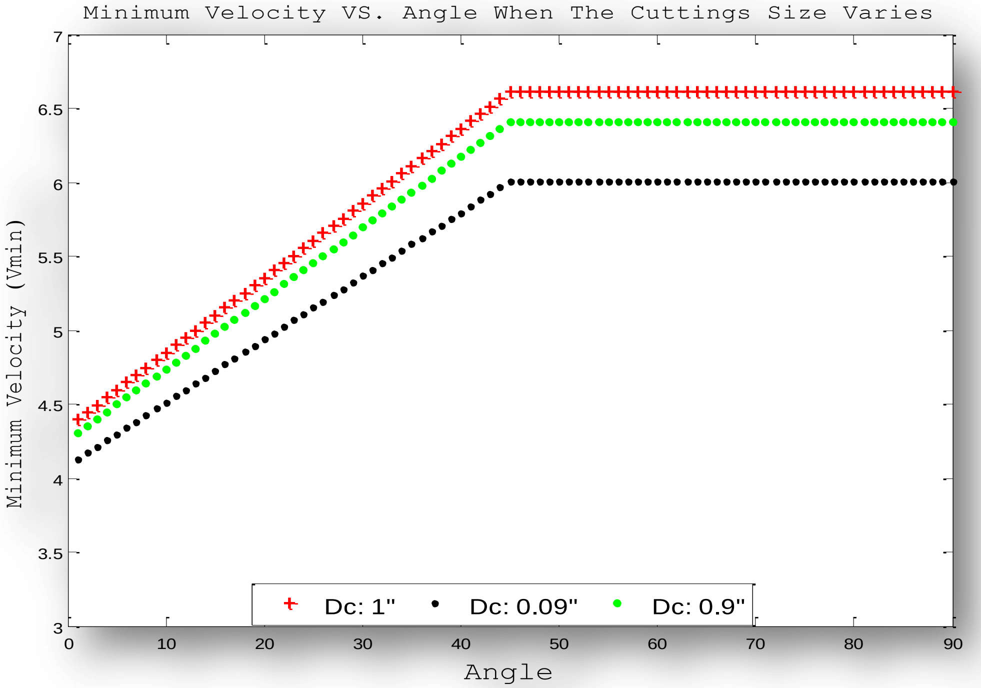

Figure (C.3): Minimum flow velocity vs. angle of inclination when the cuttings size varies.

MatLab code for flow velocity vs. angle of inclination when the cuttings size varies:

```
%Cuttings viscosity
Dpipe=2.375;
Dhole=5;
ROP=540;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
Cconc=(0.01778*ROP)+0.505;
vcut=(ROP/(36*a*Cconc));
vs1=0.1;
n=0
vsv=0.2;
while (abs(vsv-vs1)>0.001)
n=n+1
Vmin=vcut+vs1;
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=7;
YP=7;
C1=(5*YP*D1)/vmin;
u=PV+C1;
Dcut=0.175;
Pm=8.57;
Re= (928*Pm*Dcut*vs1)/u;
% calculate vs2
if (Re<3)
    f=40/Re;
elseif ((Re>3)&(Re<300))
 f=22/sqrt(Re);
else
    f=1.54;
```

```
end
Ps=19;
vsv=f*(sqrt(Dcut*((Ps-Pm)/Pm)))
vs1=((vsv+vs1)/2);
end
%end of while
RPM= 80;
for i= (1:90)
    ang(i)=i;
if (ang(i) <= 45)
    vs = vcut+(1+ (ang(i)*(600-RPM)*(3+Pm)/202500))*vsv;
else
    vs= vcut+((1+(3+Pm)*(600-RPM)/4500))*vsv;
end
    Vmin(i)= vcut+vs
end
plot(ang,Vmin)
title('Minimum Velocity VS. Angle when The Cuttings Size Varies')
xlabel('Angle')
ylabel('Minimum Velocity (Vmin)')
axis ([0,90,3.0,7])
```

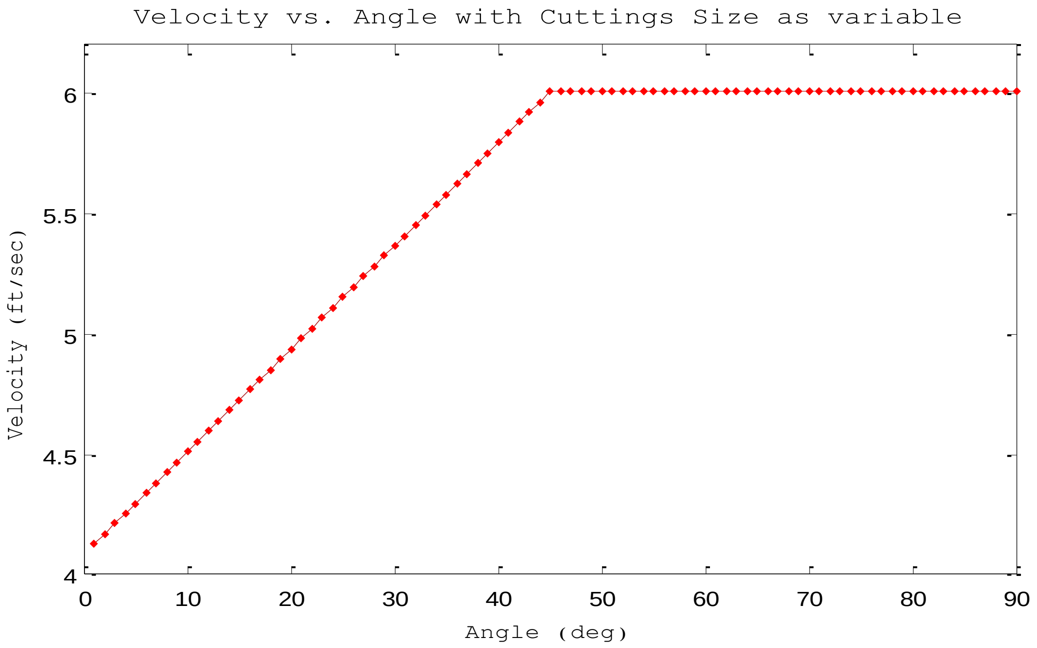

Figure (C.4): Minimum flow velocity vs. angle of inclination when the cuttings size varies.

MatLab code for flow velocity vs. angle of inclination when the mud rheology varies:

```
%Cuttings viscosity
Dpipe=2.375;
Dhole=5;
ROP=540;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
Cconc=(0.01778*ROP)+0.505;
vcut=(ROP/(36*a*Cconc));
vs1=0.1;
n=0
vsv=0.2;
while (abs(vsv-vs1)>0.001)
```

```
n=n+1
Vmin=vcut+vs1;
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=7;
YP=7;
C1=(5*YP*D1)/vmin;
u=PV+C1;
Dcut=0.175;
Pm=8.57;
Re= (928*Pm*Dcut*vs1)/u;
% calculate vs2
if (Re<3)
    f=40/Re;
elseif ((Re>3)&(Re<300))
 f=22/sqrt(Re);

else
    f=1.54;
end
Ps=19;
vsv=f*(sqrt(Dcut*((Ps-Pm)/Pm)))
vs1=((vsv+vs1)/2);
end
%end of while
RPM= 80;
for i= (1:90)
    ang(i)=i;
if (ang(i) <= 45)
    vs = vcut+(1+ (ang(i)*(600-RPM)*(3+Pm)/202500))*vsv;
else
    vs= vcut+((1+(3+Pm)*(600-RPM)/4500))*vsv;
end
    Vmin(i)= vcut+vs
end
plot(ang,Vmin)
title('Minimum Velocity VS. Angle when The Mud Viscosity Varies')
xlabel('Angle')
ylabel('Minimum Velocity (Vmin)')
%gtext('mmmm')
axis ([0,90,3.0,8])
```

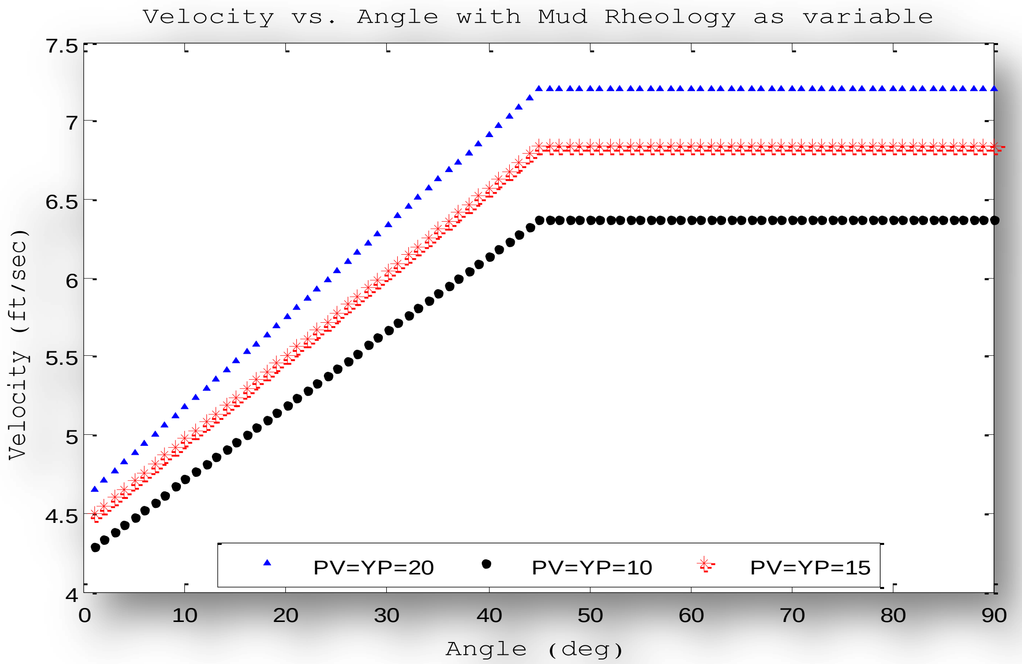

Figure (C.5): Minimum flow velocity vs. angle of inclination when the mud rheology varies.

MatLab code for flow velocity vs. angle of inclination with RPM as a variable:

```
%Cuttings viscosity
Dpipe=2.375;
Dhole=5;
ROP=540;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
Cconc=(0.01778*ROP)+0.505;
vcut=(ROP/(36*a*Cconc));
vs1=0.1
n=0
vsv=0.2;
while (abs(vsv-vs1)>0.001)
n=n+1
Vmin=vcut+vs1;
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=7;
YP=7;
C1=(5*YP*D1)/vmin;
u=PV+C1;
Dcut=0.175;
Pm=8.57;
Re= (928*Pm*Dcut*vs1)/u;
% calculate vs2
if (Re<3)
    f=40/Re;
elseif ((Re>3)&(Re<300))
 f=22/sqrt(Re);
else
    f=1.54;
```

```
end
Ps=19;
vsv=f*(sqrt(Dcut*((Ps-Pm)/Pm)))
vs1=((vsv+vs1)/2);
end
%end of while
RPM= 80;
for i= (1:90)
    ang(i)=i;
if (ang(i) <= 45)
    vs = vcut+(1+ (ang(i)*(600-RPM)*(3+Pm)/202500))*vsv;
else
    vs= vcut+((1+(3+Pm)*(600-RPM)/4500))*vsv;
end
    Vmin(i)= vcut+vs
end
plot(ang,Vmin)
title('Minimum Velocity VS. Angle when The RPM Varies')
xlabel('Angle')
ylabel('Minimum Velocity (Vmin)')
%gtext('mmmm')
axis ([0,90,3.0,8])
```

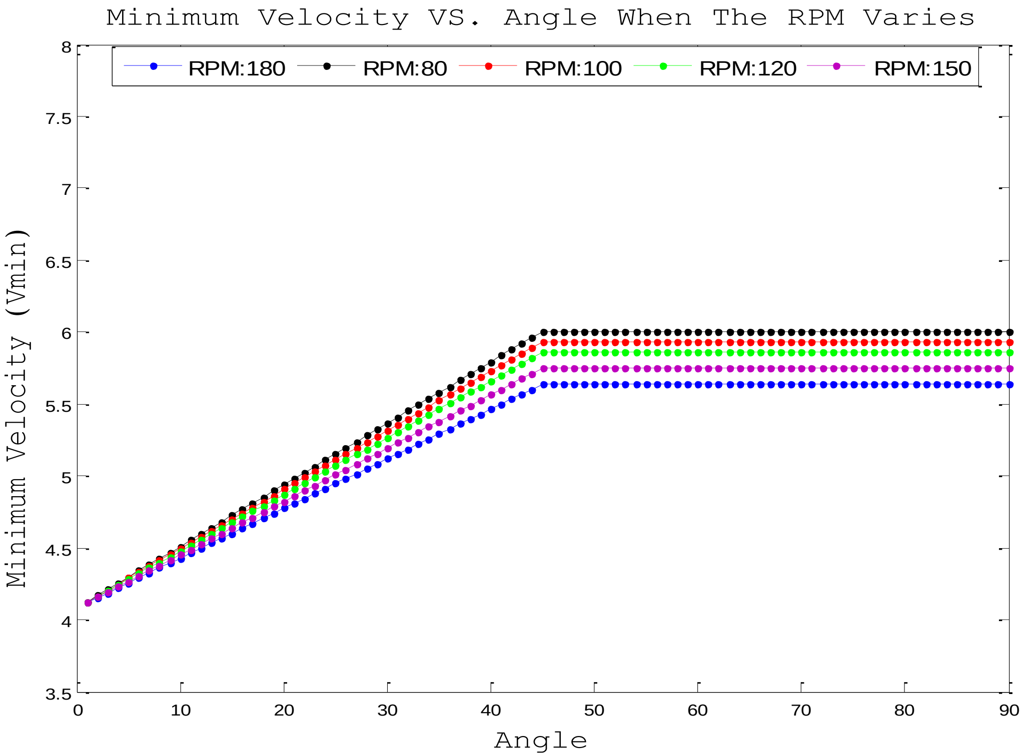

Figure (C.6): Minimum flow velocity vs. angle of inclination with RPM as a variable.

MatLab code for flow velocity vs. angle of inclination with drill-pipe diameter as a variable

```
%Cuttings viscosity
Dpipe=3.4;
Dhole=5;
ROP=54;
Dtot=Dpipe/Dhole;
```

```
a=1-(Dtot)^2;
Cconc=(0.01778*ROP)+0.505;
vcut=(ROP/(36*a*Cconc));
vs1=0.1;
n=0
vsv=0.2;
while (abs(vsv-vs1)>0.001)
n=n+1
Vmin=vcut+vs1;
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=7;
YP=7;
C1=(5*YP*D1)/Vmin;
u=PV+C1;
Dcut=0.175;
Pm=8.57;
Re= (928*Pm*Dcut*vs1)/u;
% calculate vs2
if (Re<3)
    f=40/Re;
elseif ((Re>3)&(Re<300))
 f=22/sqrt(Re);
else
    f=1.54;
end
Ps=19;
vsv=f*(sqrt(Dcut*((Ps-Pm)/Pm)))
vs1=((vsv+vs1)/2);
end
%end of while
RPM= 80;
for i= (1:90)
    ang(i)=i;
if (ang(i) <= 45)
    vs = vcut+(1+ (ang(i)*(600-RPM)*(3+Pm)/202500))*vsv;
else
    vs= vcut+((1+(3+Pm)*(600-RPM)/4500))*vsv;
end
    Vmin(i)= vcut+vs
end
plot(ang,Vmin,ang,a1,ang,a2)
title('Velocity vs. Angle with Drill-Pipe Diameter as variable')
xlabel('Angle (deg)')
ylabel('Velocity (ft/sec)')
%axis ([0,90,4,6.2])
```

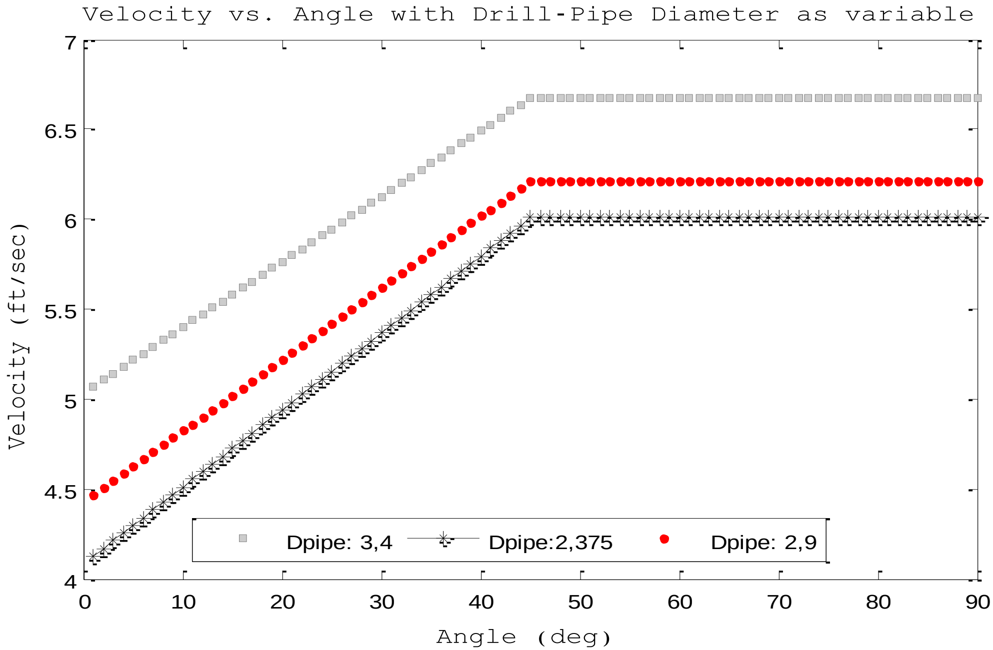

Figure (C.7): Minimum flow velocity vs. angle of inclination with drill-pipe diameter as a variable.

Appendix D

In this appendix, MatLab codes that were used to draw various graphs for predictions of required flow rates using Larsen's model that are presented in chapter 8.3.1 are displayed.

MatLab code for flow velocity vs. angle of inclinations with ROP as a variable:

```
%Cuttings viscosity
Dpipe=5;
Dhole=8.5;
ROP=164;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
b=0.64+(18.16/ROP);
vcut=1/(a*b);
%Assume vs1
vs1=1.3;
vs2=vs1;
n=0
while (vs2-vs1)<=0.01
Vcrit=vs1+vcut;
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=7;
YP=7;
C1=5*YP*D1/Vcrit;
u=PV+C1;
% calculate vs2
if (u<53)
vs2=(0.00516*u)+3.006;
else
 vs2=0.02554*(u-53)+3.28;
end
n=n+1
end
%Correction factor for angle
ang=(55:1:90);
w=(0.0342*(ang));
L=(0.000233*(ang.^2));
Cang=(w-L-0.213);
%correction factor for cuttings size
Dcutt=0.3;
Csize=-1.04*(Dcutt)+1.286;
%Correction factor for mud weight
% pm= mud weight (ppg)
pm=10.83;
if (pm>=8.57);
Cmwt=(1-0.0333*(pm-8.7));
else
    Cmwt=1;
end
Vslip=(vs2*Cang*Csize*Cmwt);
%plot(ang,vslip)
Vmin= (Vslip+vcut)
plot(ang,Vmin,ang,a1,ang,a2)
title('Velocity vs. Angle with ROP as a variable')
xlabel('Angle (deg)')
ylabel('Velocity (ft/sec)')
axis ([55,90,3.75,6]
```

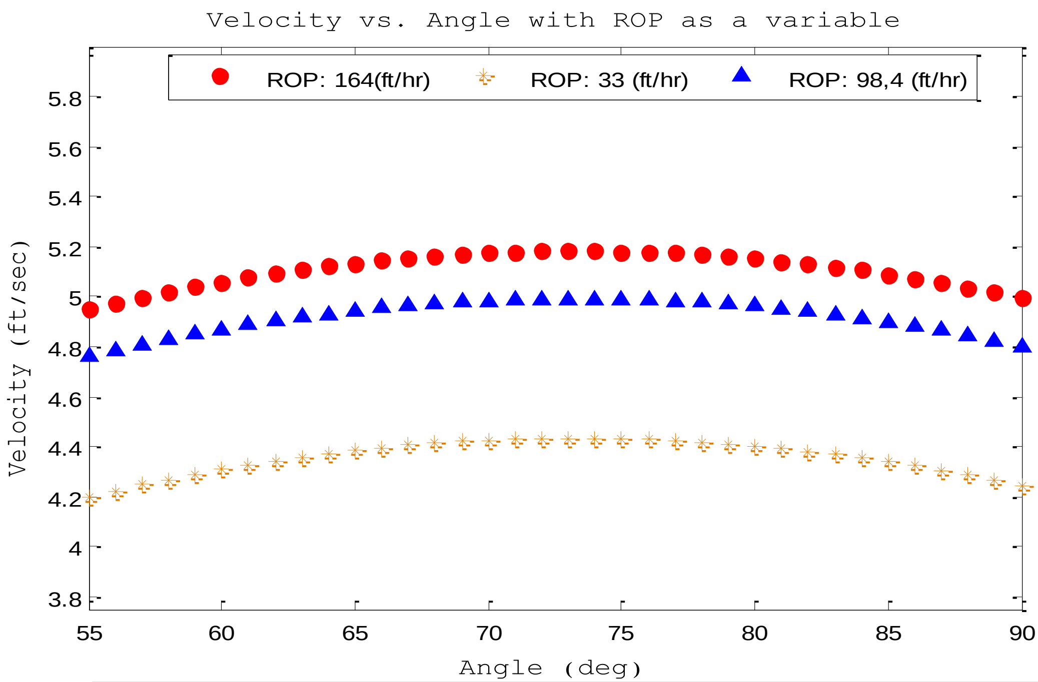

Figure (D.1): Flow Velocity vs. angle of inclinations with ROP as a variable.

MatLab code for flow velocity vs. angle of inclination with mud weight as a variable:

```
%Cuttings viscosity
Dpipe=5;
Dhole=8.5;
ROP=33;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
b=0.64+(18.16/ROP);
vcut=1/(a*b);
%Assume vs1
vs1=1.3;
vs2=vs1;
n=0
while (vs2-vs1)<=0.01
Vcrit=vs1+vcut;
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=7;
YP=7;
C1=5*YP*D1/Vcrit;
u=PV+C1;
% calculate vs2
if (u<53)
vs2=(0.00516*u)+3.006;
else
 vs2=0.02554*(u-53)+3.28;
end
n=n+1
end
%Correction factor for angle
ang=(55:1:90);
w=(0.0342*(ang));
```

```
L=(0.000233*(ang.^2));
Cang=(w-L-0.213);
%correction factor for cuttings size
Dcutt=0.3;
Csize=-1.04*(Dcutt)+1.286;
%Correction factor for mud weight
% pm= mud weight (ppg)
pm=15;
if (pm>=8.57);
Cmwt=(1-0.0333*(pm-8.7));
else
    Cmwt=1;
end
Vslip=(vs2*Cang*Csize*Cmwt);
%plot(ang,vslip)
Vmin= (Vslip+vcut)
plot(ang,Vmin,ang,a1,ang,a2)
title('Velocity vs. Angle with Mud Weight as a variable')
xlabel('Angle (deg)')
ylabel('Velocity (ft/sec)')
axis ([55,90,3,6])
```

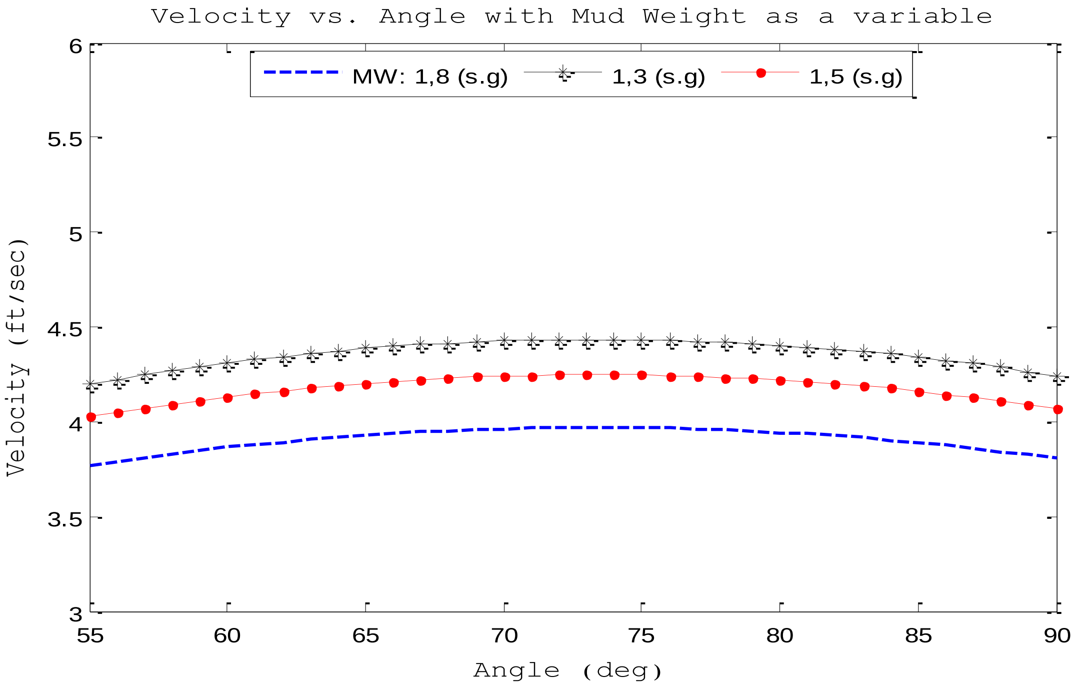

Figure (D.2): Flow velocity vs. angle of inclination with mud weight as a variable.

MatLab code for flow velocity vs. angle of inclinations with cuttings size as a variable:

```
%Cuttings viscosity
Dpipe=5;
Dhole=8.5;
ROP=33;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
b=0.64+(18.16/ROP);
vcut=1/(a*b);
 %Assume vs1
```

```
vs1=1.3;
vs2=vs1;
 n=0
while (vs2-vs1)<=0.01
 Vcrit=vs1+vcut;
 %Apparent Viscosity
D1=Dhole-Dpipe;
PV=7;
YP=7;
C1=5*YP*D1/Vcrit;
u=PV+C1;
 % calculate vs2
if (u<53)
  vs2=(0.00516*u)+3.006;
 else
 vs2=0.02554*(u-53)+3.28;
 end
n=n+1
end
 %Correction factor for angle
ang=(55:1:90);
w=(0.0342*(ang));
L=(0.000233*(ang.^2));
Cang=(w-L-0.213);
 %correction factor for cuttings size
Dcutt=0.1;
Csize=-1.04*(Dcutt)+1.286;
%Correction factor for mud weight
% pm= mud weight (ppg)
pm=10.83;
if (pm>=8.57);
Cmwt=(1-0.0333*(pm-8.7));
else
    Cmwt=1;
end
Vslip=(vs2*Cang*Csize*Cmwt);
%plot(ang,vslip)
Vmin= (Vslip+vcut)
plot(ang,Vmin,ang,a1,ang,a2)
title('Velocity vs. Angle with Cuttings Size as a variable')
xlabel('Angle (deg)')
ylabel('Velocity (ft/sec)')
axis ([55,90,3,6])
```

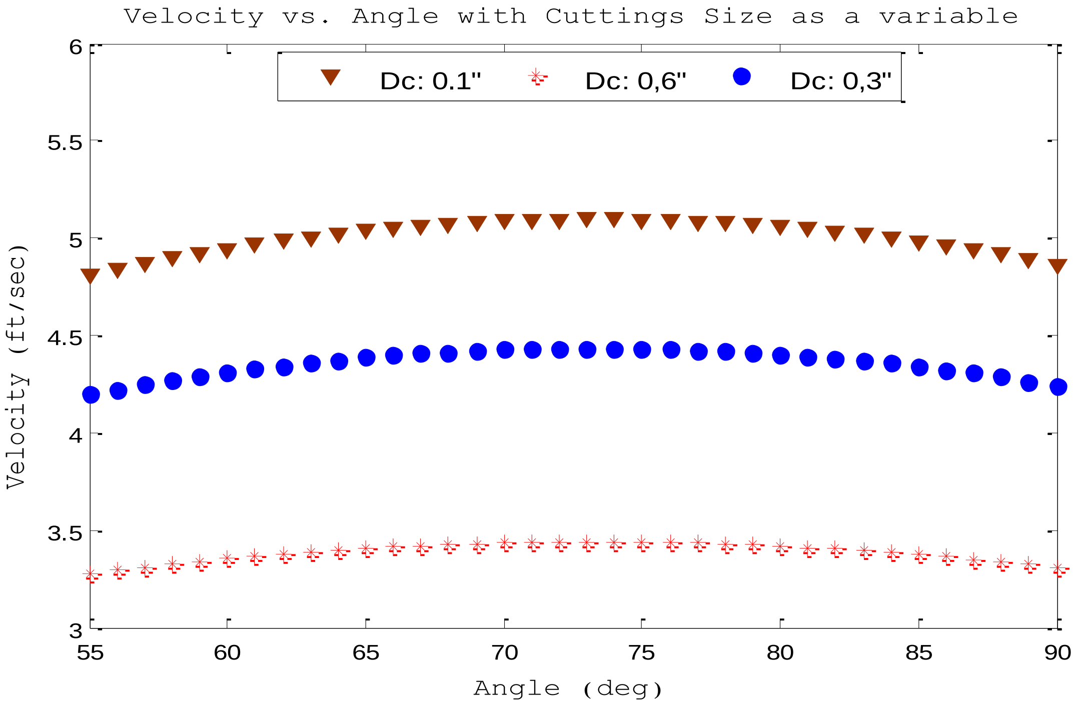

Figure (D.3): Flow velocity vs. angle of inclinations with cuttings size as a variable.

MatLab code for flow velocity vs. angle of inclinations with mud rheology as a variable:

```
%Cuttings viscosity
Dpipe=5;
Dhole=8.5;
ROP=33;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
b=0.64+(18.16/ROP);
vcut=1/(a*b);
%Assume vs1
vs1=1.3;
vs2=vs1;
 n=0
while (vs2-vs1)<=0.01
 Vcrit=vs1+vcut;
 %Apparent Viscosity
D1=Dhole-Dpipe;
PV=11;
YP=11;
C1=5*YP*D1/Vcrit;
u=PV+C1;
 % calculate vs2
if (u<53)
vs2=(0.00516*u)+3.006;
else
 vs2=0.02554*(u-53)+3.28;
end
n=n+1
end
%Correction factor for angle
ang=(55:1:90);
```

```
w=(0.0342*(ang));
L=(0.000233*(ang.^2));
Cang=(w-L-0.213);
%correction factor for cuttings size
Dcutt=0.3;
Csize=-1.04*(Dcutt)+1.286;
%Correction factor for mud weight
% pm= mud weight (ppg)
pm=10.83;
if (pm>=8.57);
Cmwt=(1-0.0333*(pm-8.7));
else
    Cmwt=1;
end
Vslip=(vs2*Cang*Csize*Cmwt);
%plot(ang,vslip)
 Vmin= (Vslip+vcut)
 plot(ang,Vmin,ang,a1,ang,a2)
title('Velocity vs. Angle with Mud Rheology as a variable')
xlabel('Angle (deg)')
ylabel('Velocity (ft/sec)')
axis ([55,90,4,6.5])
```

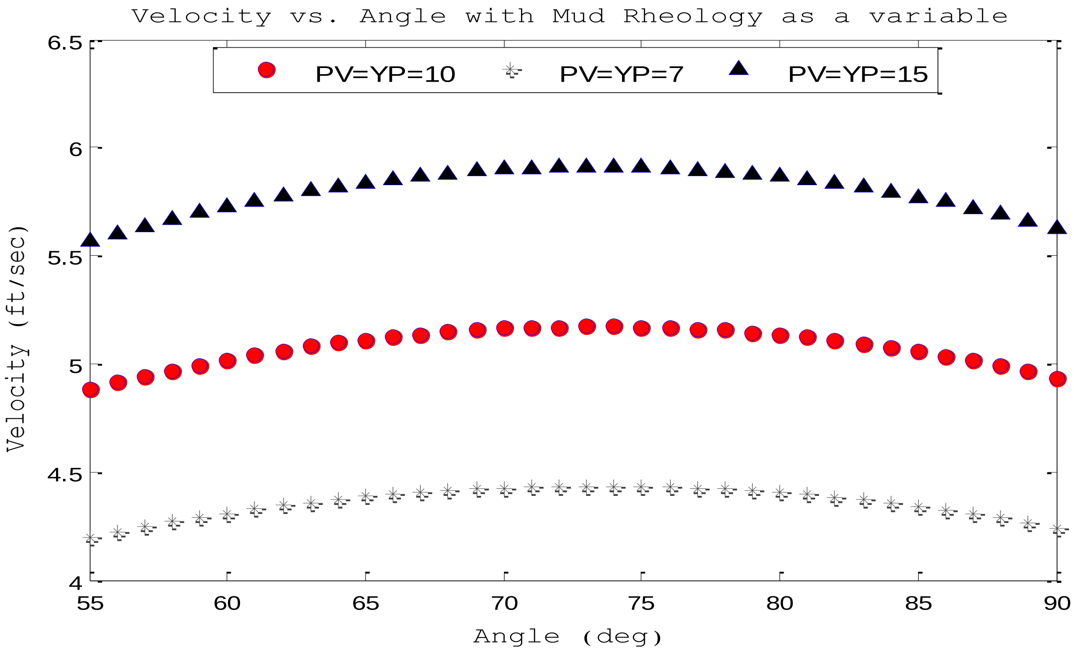

Figure (D.4): Flow velocity vs. angle of inclinations with mud rheology as a variable.

Appendix E

In this appendix, MatLab codes that were used to draw various graphs for predictions of required flow rates using Rubiandini's model that are presented in chapter 8.3.2 are displayed.

MatLab code for velocity vs. angle of inclination with ROP as a variable:

```
%Cuttings viscosity
Dpipe=5;
Dhole=8.5;
ROP=164;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
Cconc=(0.01778*ROP)+0.505;
vcut=(ROP/(36*a*Cconc));
 vs1=0.1;
 n=0
vsv=0.2;
while (abs(vsv-vs1)>0.001)
n=n+1
 vmin=vcut+vs1;
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=7;
YP=7;
C1=(5*YP*D1)/vmin;
u=PV+C1;
 Dcut=0.3;
Pm=10.83;
Re= (928*Pm*Dcut*vs1)/u;
 % calculate vs2
if (Re<3)
 f=40/Re;
 elseif ((Re>3)&(Re<300))
 f=22/sqrt(Re);
 else
    f=1.54;
end
Ps=19;
vsv=f*(sqrt(Dcut*((Ps-Pm)/Pm)))
vs1=((vsv+vs1)/2);
end
%end of while
 RPM= 80;
 for i= (1:90)
    ang(i)=i;
   if (ang(i) <= 45)
     vs = vcut+(1+ (ang(i)*(600-RPM)*(3+Pm)/202500))*vsv;
else
    vs= vcut+((1+(3+Pm)*(600-RPM)/4500))*vsv;
 end
    Vmin(i)= vcut+vs
   end
plot(ang,Vmin,ang,a1,ang,a2)
 title('Velocity vs. Angle with ROP as a variable')
xlabel('Angle (deg)')
ylabel('Velocity (ft/sec)')
%axis ([0,90,4,6.2])
```

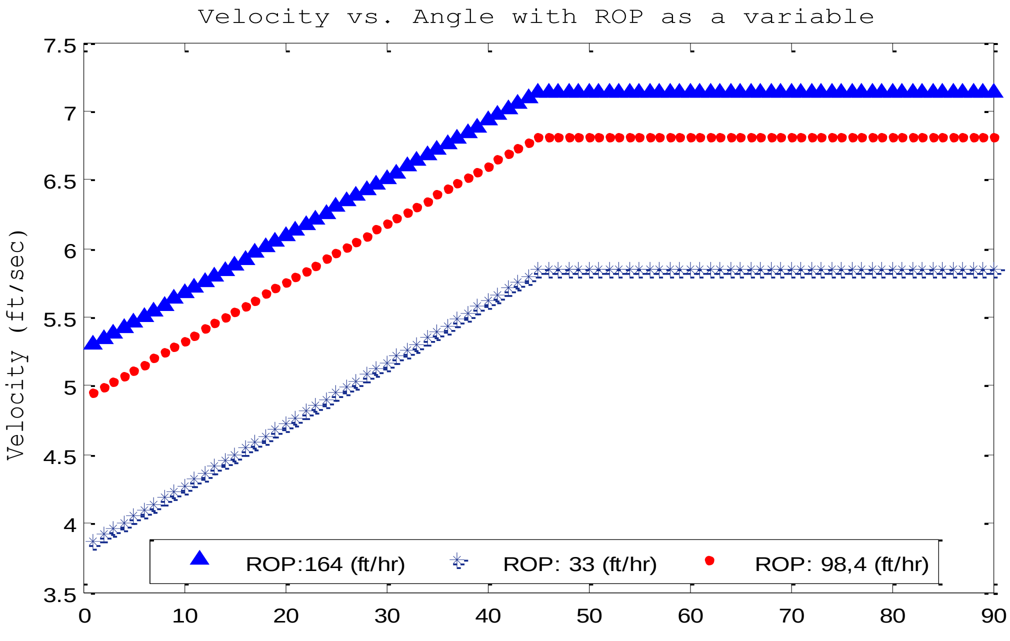

Figure (E.1): Flow velocity vs. angle of inclination with ROP as a variable.

MatLab code for flow velocity vs. angle of inclination with mud weight as a variable:

```
%Cuttings viscosity
Dpipe=5;
Dhole=8.5;
ROP=33;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
Cconc=(0.01778*ROP)+0.505;
vcut=(ROP/(36*a*Cconc));
vs1=0.1;
n=0
vsv=0.2;
while (abs(vsv-vs1)>0.001)
n=n+1
vmin=vcut+vs1;
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=7;
YP=7;
C1=(5*YP*D1)/vmin;
u=PV+C1;
Dcut=0.3;
Pm=15;
Re= (928*Pm*Dcut*vs1)/u;
% calculate vs2
if (Re<3)
    f=40/Re;
elseif ((Re>3)&(Re<300))
 f=22/sqrt(Re);
else
    f=1.54;
end
Ps=19;
```

```
vsv=f*(sqrt(Dcut*((Ps-Pm)/Pm)))
vs1=((vsv+vs1)/2);
end
%end of while
RPM= 80;
for i= (1:90)
    ang(i)=i;
if (ang(i) <= 45)
    vs = vcut+(1+ (ang(i)*(600-RPM)*(3+Pm)/202500))*vsv;
else
    vs= vcut+((1+(3+Pm)*(600-RPM)/4500))*vsv;
end
    Vmin(i)= vcut+vs
end
plot(ang,Vmin,ang,a1,ang,a2)
title('Velocity vs. Angle with Mud Weight as a variable')
xlabel('Angle (deg)')
ylabel('Velocity (ft/sec)')
%axis ([0,90,4,6.2])
```

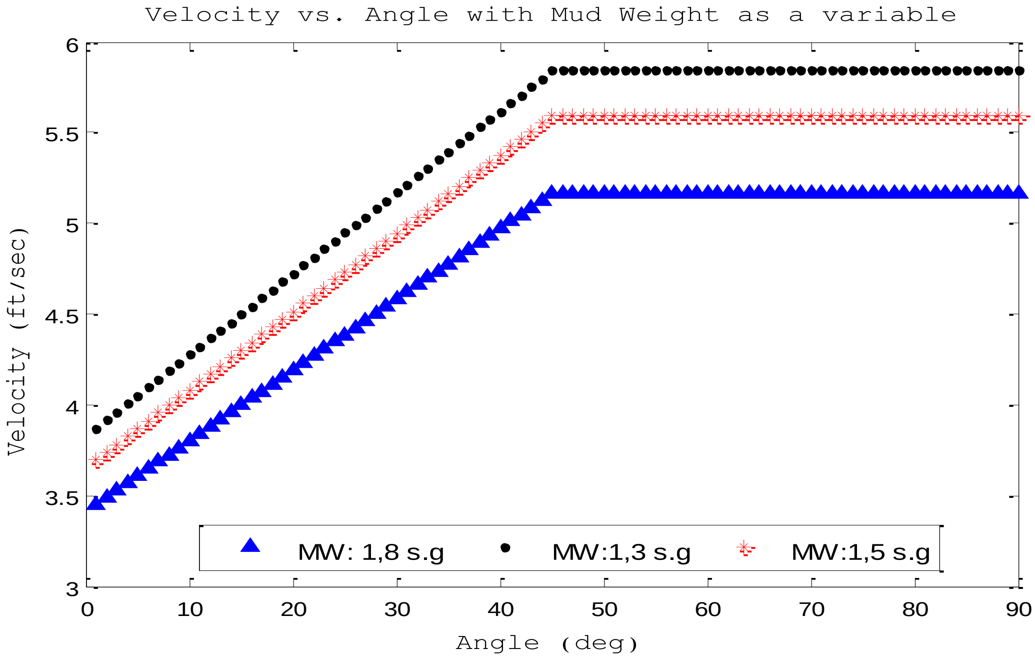

Figure (E.2): Flow velocity vs. angle of inclination with mud weight as a variable.

MatLab code for flow velocity vs. angle of inclination with mud rheology as a variable:

```
%Cuttings viscosity
Dpipe=5;
Dhole=8.5;
ROP=33;
Dtot=Dpipe/Dhole;
a=1-(Dtot)^2;
Cconc=(0.01778*ROP)+0.505;
vcut=(ROP/(36*a*Cconc));
vs1=0.1;
n=0
vsv=0.2;
while (abs(vsv-vs1)>0.001)
n=n+1
vmin=vcut+vs1;
```

```
%Apparent Viscosity
D1=Dhole-Dpipe;
PV=7;
YP=7;
C1=(5*YP*D1)/vmin;
u=PV+C1;
Dcut=1.5;
Pm=10.83;
Re= (928*Pm*Dcut*vs1)/u;
% calculate vs2
if (Re<3)
 f=40/Re;
elseif ((Re>3)&(Re<300))
 f=22/sqrt(Re);
else
    f=1.54;
end
Ps=19;
vsv=f*(sqrt(Dcut*((Ps-Pm)/Pm)))
vs1=((vsv+vs1)/2);
end
%end of while
RPM= 80;for i= (1:90)
    ang(i)=i;
if (ang(i) <= 45)
    vs = vcut+(1+ (ang(i)*(600-RPM)*(3+Pm)/202500))*vsv;
else
    vs= vcut+((1+(3+Pm)*(600-RPM)/4500))*vsv;
end
    Vmin(i)= vcut+vs
end
plot(ang,Vmin,ang,a1,ang,a2)
title('Velocity vs. Angle with Mud Rheology as a variable')
xlabel('Angle (deg)')
ylabel('Velocity (ft/sec)')
%axis ([0,90,4,6.2])
```

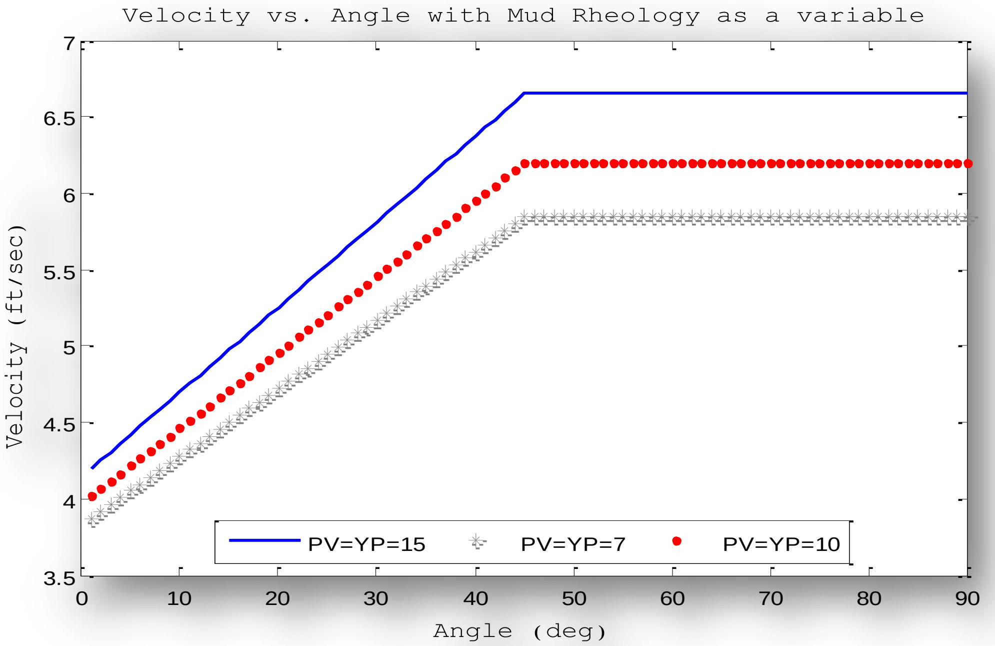

Figure (E.3): Flow velocity vs. angle of inclination with mud rheology as a variable.

Appendix F

In this appendix, hole cleaning chart representing lag depth vs. drilled volume that is documented in chapter 9.5 is displayed.

HOLE CLEANING CHART													**Loss Factor**
12 ¼" Hole													**1**
Hole Volume		**0,076**				**Drill pipe displacement factor**				**0,00474**			**1,41**
													4
Time	Lag depth	Act. vol.	Flow	Out of active (+)	Into active (+)	Observed vol. chg.	Comments (Act.pits,pills, CBU,sliding, etc)	Drilled volume	**Steel vol. 12 ¼" " DP**	**Teor. Vol. dry cuttings.**	**Dry vol.+40% mud on cuttings**	**Total Volume Ratio**	**Teor. vol. chg. +300% .**
02:50	1273	46,5	3050			0		0,00	**0,01**	**0,00**	**0,00**	**0,00**	**0,01**
03:50	1296	47,9	3060		3	-1,6		-1,75	**0,11**	**-1,63**	**-2,35**	**0,98**	**-6,88**
05:58	1352	91,81	3220		47	-4,69		-6,00	**0,38**	**-5,62**	**-8,09**	**0,84**	**-23,64**
06:21	1361	90,8	3540			-5,7		-6,69	**0,42**	**-6,27**	**-9,01**	**0,92**	**-26,33**
06:57	1384	89,5	3550			-7		-8,44	**0,53**	**-7,90**	**-11,36**	**0,89**	**-33,21**
07:56	1415	86,1	3650			-10,4	Increase flow	-10,79	**0,68**	**-10,11**	**-14,54**	**1,03**	**-42,49**
09:11	1458	82,1	3970			-14,4		-14,06	**0,88**	**-13,18**	**-18,94**	**1,09**	**-55,36**
10:13	1502	80,1	3400			-16,4		-17,40	**1,09**	**-16,31**	**-23,45**	**1,00**	**-68,53**
11:12	1515	71,9	3845			-24,6		-18,39	**1,15**	**-17,24**	**-24,78**	**1,40**	**-72,42**
12:04	1538	82,8	3601		23,3	-37	large mud loss	-20,14	**1,26**	**-18,88**	**-27,14**	**1,90**	**-79,30**
16:05	1661	80,1	3864			-39,7		-29,49	**1,84**	**-27,64**	**-39,73**	**1,41**	**-116,11**
16:45	1685	77,6	3860			-42,2		-31,31	**1,96**	**-29,35**	**-42,19**	**1,41**	**-123,29**
17:41	1721	75,8	3845			-44		-34,05	**2,13**	**-31,92**	**-45,88**	**1,35**	**-134,06**
18:35	1754	72,9	3816			-46,9		-36,56	**2,28**	**-34,27**	**-49,26**	**1,35**	**-143,94**
19:45	1790	69,4	3822			-50,4		-39,29	**2,46**	**-36,84**	**-52,95**	**1,35**	**-154,71**
21:05	1844	88,42	3841		26	-57,38		-43,40	**2,71**	**-40,68**	**-58,48**	**1,38**	**-170,87**
22:35	1902,9	83,88	3812		6	-67,92		-47,87	**2,99**	**-44,88**	**-64,51**	**1,48**	**-188,50**
23:25	1934	81,3	3800			-70,5		-50,24	**3,14**	**-47,10**	**-67,69**	**1,47**	**-197,81**
01:35	1992	76,9	3800			-74,9		-54,64	**3,41**	**-51,23**	**-73,63**	**1,43**	**-215,16**
03:35	2075	69,2	3805			-82,6		-60,95	**3,81**	**-57,15**	**-82,14**	**1,42**	**-240,00**
04:13	2097	66,98	3509			-84,82		-62,62	**3,91**	**-58,71**	**-84,39**	**1,42**	**-246,59**
05:18	2135	61,5	3500			-90,3		-65,51	**4,09**	**-61,42**	**-88,28**	**1,44**	**-257,96**
06:04	2164	97,4	3800		37,3	-91,7		-67,72	**4,23**	**-63,49**	**-91,25**	**1,42**	**-266,64**

06:25	2169	85,10	3800	10,8		-93,2		-68,10	**4,25**	**-63,84**	**-91,76**	**1,43**	**-268,13**
07:58	2232	79,20	3929			-99,1		-72,88	**4,55**	**-68,33**	**-98,22**	**1,42**	**-286,99**
09:20	2295	73,40	3770			-104,9		-77,67	**4,85**	**-72,82**	**-104,67**	**1,41**	**-305,84**
10:16	2338	69,40	3820			-108,9		-80,94	**5,05**	**-75,89**	**-109,07**	**1,41**	**-318,71**
11:12	2388	62,49	3825			-115,81		-84,74	**5,29**	**-79,45**	**-114,19**	**1,43**	**-333,67**
12:12	2428	59,43	3821			-118,87		-87,78	**5,48**	**-82,30**	**-118,29**	**1,42**	**-345,64**
13:20	2482	76,90	3731		20	-121,4		-91,88	**5,74**	**-86,15**	**-123,82**	**1,38**	**-361,80**
14:09	2515	72,00	3759			-126,3		-94,39	**5,89**	**-88,50**	**-127,20**	**1,40**	**-371,68**
15:11	2568	66,60	3811			-131,7		-98,42	**6,14**	**-92,28**	**-132,63**	**1,40**	**-387,54**
16:30	2626	59,27	3746			-139,03		-102,83	**6,42**	**-96,41**	**-138,57**	**1,41**	**-404,89**
17:20	2664	68,60	3718		13,2	-142,9		-105,72	**6,60**	**-99,12**	**-142,46**	**1,41**	**-416,27**
18:36	2713	62,9	3794	1,4		-147,2		-109,44	**6,83**	**-102,61**	**-147,48**	**1,41**	**-430,93**
20:02	2769	76,0	3300		19,5	-153,65		-113,70	**7,10**	**-106,60**	**-153,22**	**1,41**	**-447,69**
22:10	2822	68,7	3300			-160,9		-117,72	**7,35**	**-110,38**	**-158,64**	**1,43**	**-463,55**
22:46	2835	67,2	3340			-162,4		-118,71	**7,41**	**-111,30**	**-159,98**	**1,43**	**-467,44**
00:50	2899	58,4	3778			-171,2		-123,58	**7,71**	**-115,86**	**-166,53**	**1,45**	**-486,59**
01:57	2926	45,8	3750	9,1		-174,7		-125,63	**7,84**	**-117,79**	**-169,30**	**1,45**	**-494,67**
02:16	2938	91,5	3780		47	-176		-126,54	**7,90**	**-118,64**	**-170,52**	**1,45**	**-498,26**
03:42	2968	86,2	3800			-181,3		-128,82	**8,04**	**-120,78**	**-173,60**	**1,47**	**-507,24**
04:18	2974,0	85,3	3816			-182,2		-129,28	**8,07**	**-121,21**	**-174,21**	**1,47**	**-509,04**
05:10	2991,0	82,5	3800			-185		-130,57	**8,15**	**-122,42**	**-175,95**	**1,48**	**-514,12**
05:45	2997,0	81,6	3800			-185,9		-131,02	**8,18**	**-122,85**	**-176,57**	**1,48**	**-515,92**
06:18	3001,0	80,2	3800			-187,3		-131,33	**8,20**	**-123,13**	**-176,98**	**1,49**	**-517,12**
07:15	3021,0	77,2	3771			-190,33		-132,85	**8,29**	**-124,56**	**-179,03**	**1,50**	**-523,10**
08:15	3041,0	75,0	3769			-192,5		-134,37	**8,39**	**-125,98**	**-181,07**	**1,50**	**-529,09**
09:36	3079,0	69,6	3801			-197,89		-137,26	**8,57**	**-128,69**	**-184,97**	**1,50**	**-540,46**
10:23	3097,0	67,3	3752			-200,2		-138,62	**8,65**	**-129,97**	**-186,81**	**1,51**	**-545,85**
11:23	3124,0	56,0	3822	7,3		-204,2		-140,68	**8,78**	**-131,90**	**-189,57**	**1,51**	**-553,93**