GRAPHICAL EVALUATION OF CUTTINGS TRANSPORT IN DEVIATED WELLS USING BINGHAM PLASTIC FLUID MODEL

BY

ABIMBOLA MAJEED OLASUNKANMI

A THESIS SUBMITTED TO THE

DEPARTMENT OF PETROLEUM ENGINEERING

AFRICAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

ABUJA, NIGERIA

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF DEGREE OF MASTER OF SCIENCE

NOVEMBER 2011

GRAPHICAL EVALUATION OF CUTTINGS TRANSPORT IN DEVIATED WELLS USING BINGHAM PLASTIC MODEL

BY

ABIMBOLA MAJEED OLASUNKANMI

RECOMMENDED:

Advisory Committee Chair:

Professor Godwin A. Chukwu

Advisory Committee Member:

Dr. Samuel O. Osisanya

Advisory Committee Member:

Dr. Debasmita Misra

APPROVED:

Director of the Department of Petroleum Engineering **Date**

Chief Academic Officer **Date**

DEDICATION

This thesis is dedicated to Almighty Allah for His infinite mercy in seeing me through my Master of Science Degree in Petroleum Engineering and my personal affairs. I give Him all the glory. To my sweet mother, step mother, late father, late step mother, siblings, maternal grandmother and mother-in-law. Specially, to my loving wife and my baby girl, Raheemah, for being there for me always. Finally, to my well-wishers, may Allah bless you all

ACKNOWLEDGMENT

I wish to express my appreciation of the efforts of my major supervisor, Professor G. A. Chukwu for his invaluable support and guidance towards the completion of this research, my thesis advisory committee members: Dr. S. O. Osisanya, University of Oklahoma, Norman and Dr. D. Misra, University of Alaska, Fairbanks for their acceptance to serve in the supervisory committee and their suggestions towards the completion of this work. Most importantly, to Habibu Engineering Nigeria Limited, Abuja, for the award of scholarship into the Master of Science Degree program through Mr. Jide Babatunde. Special thanks to Mr. Saheed Adewale, for his suggestion on that fateful day (14/6/2010).

ABSTRACT

The transportation of cuttings and efficient hole cleaning are indispensible in any drilling program. This is because a successful drilling operation is the key to a profitable business in the oil and gas sector. A successful drilling program is as a result of an efficiently cleaned hole. Cuttings transport efficiency in vertical and deviated wellbores has been reported to depend on the following factors: hole geometry and inclination, average fluid velocity, fluid flow regime, drill pipe rotation, pipe eccentricity, fluid properties and rheology, cuttings size and shape, cuttings concentration, cuttings transport velocity, rate of penetration and multiphase flow effect.

In this work, the effects of mud flow rate, ROP, annular clearance, mud and cuttings densities on annular fluid velocity, transport ratio and mean mud density on cuttings transportation are investigated. Correlations based on the work of Larsen et al (1997) and Borgoyne et al. (1986) are developed and used to generate nomographs. The data used by Larsen et al. (1997) and real well data in the work of Ranjbar (2010) were used to validate the equations used in this study.

The results obtained from the new equations closely conform to those of Larsen et al (1997) method and also predicted the required flow rate in the example well data of Ranjbar (2010).

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Page

LIST OF APPENDICES

Page

CHAPTER ONE

INTRODUCTION

Transportation of cuttings and efficiency of the hole cleaning has been one of the major concerns of stake holders in the oil and gas industry. This is because a successful drilling program is a key to a productive and profitable oil and gas business. A successful drilling program is as a result of an efficiently cleaned hole. On the other hand, a poor or inefficient hole cleaning implies accumulation of cuttings or formation of cuttings bed in the well. This often leads to decreased rate of penetration, increased cost of drilling, fractured formation, increased plastic viscosity of mud as a result of grinding of cuttings and stuck pipe. Hole cleaning is effected primarily with a drilling fluid. The function of a drilling fluid is chiefly the transportation of cuttings out of a drilled hole. Other major functions of a drilling fluid in a drilling program include: cooling and lubricating the bit and drill string, cleaning of the bottom of the hole, removal of cuttings from mud at the surface, minimizing of formation damage, controlling of formation pressures, hole integrity maintenance, improving of drilling rate, aiding of well logging operations, minimizing contamination problems, torque, drag, pipe sticking and corrosion of the drill string, casings and tubings.

Cuttings transport studies in vertical and deviated wells have been reported over the last four decades and are still on going. Among the conclusions as will be seen in the literature from the numerous studies reported are that cuttings transport efficiency of a drilling program depends on the following factors:

- Hole geometry and inclination

- Average fluid velocity
- Fluid flow regime (lamina or turbulent)
- Drill pipe rotation
- Pipe eccentricity
- Fluid properties and rheology
- Cuttings Size and Shape
- Cuttings Concentration
- Cutting Transport Velocity
- Rate of Penetration
- Multiphase flow effect

Correlations and charts have been developed by researchers (Tomren et al., 1986, Gavignet and Sobey, 1989, Peden et al., 1990, Luo et al., 1994, Larsen et al., 1997, Kamp and Rivero, 1999, Mirhaj et al. 2007) on the parameters that affect carrying capacity of fluid and efficient hole cleaning in vertical and deviated wells. Some of these correlations are empirical (Peden et al., 1990, Luo et al., 1994, Larsen et al., 1997, Mirhaj et al. 2007) while others are mechanistic (Gavignet and Sobey, 1989, Kamp and Rivero, 1999). Besides, the charts are usually developed for field applications. These are necessary in predicting and optimizing a drilling program. Luo et al. (1994), for example, developed simple charts for determining hole cleaning requirements in deviated wells. The developed charts relate plastic viscosity with yield points, mud flow rate with rate of penetration for different hole sizes and transport indices, critical flow rate with yield point and washout hole size.

Adari et al. (2000) arranged the parameters controlling cuttings transport according to their order of importance to hole cleaning as shown in figure 1.1. From the figure, it is shown that volumetric flow rate, fluid rheology, and rate of penetration (ROP) have the highest control on the efficiency of hole cleaning. Fluid rheology comprises plastic viscosity and yield point. Rate of penetration expresses the depth of the hole that is removed per unit of time.

Transport ratio is defined as the ratio of cuttings transport velocity to the annular fluid velocity. Mathematically, it is stated as:

$$F_T = \frac{\bar{v}_T}{\bar{v}_a} \tag{1.1}$$

But $\bar{v}_T = \bar{v}_a - \bar{v}_{sl}$, substituting, gives

$$F_T = 1 - \frac{\bar{v}_{sl}}{\bar{v}_a} \tag{1.2}$$

Where F_T is the transport ratio, $\bar{v}_T$ is the cuttings transport velocity, $\bar{v}_{sl}$ is the particle slip velocity and $\bar{v}_a$ is the fluid average annular velocity.

Apart from the work of Larsen et al (1997) and Mirhaj et al. (2007), studies relating annular velocity, transport ratio to rate of penetration and annular clearance for various mud flow rates have not been reported in the literature, thus, the justification for this research work.

1.1 RESEARCH OBJECTIVES

The objectives of this research work include:

- To review the works that have been done on cuttings transport and hole cleaning.
- To investigate the effects of flow rates, rate of penetration on annular velocities and transport ratio for different hole sizes (annular clearance) using Bingham plastic fluid

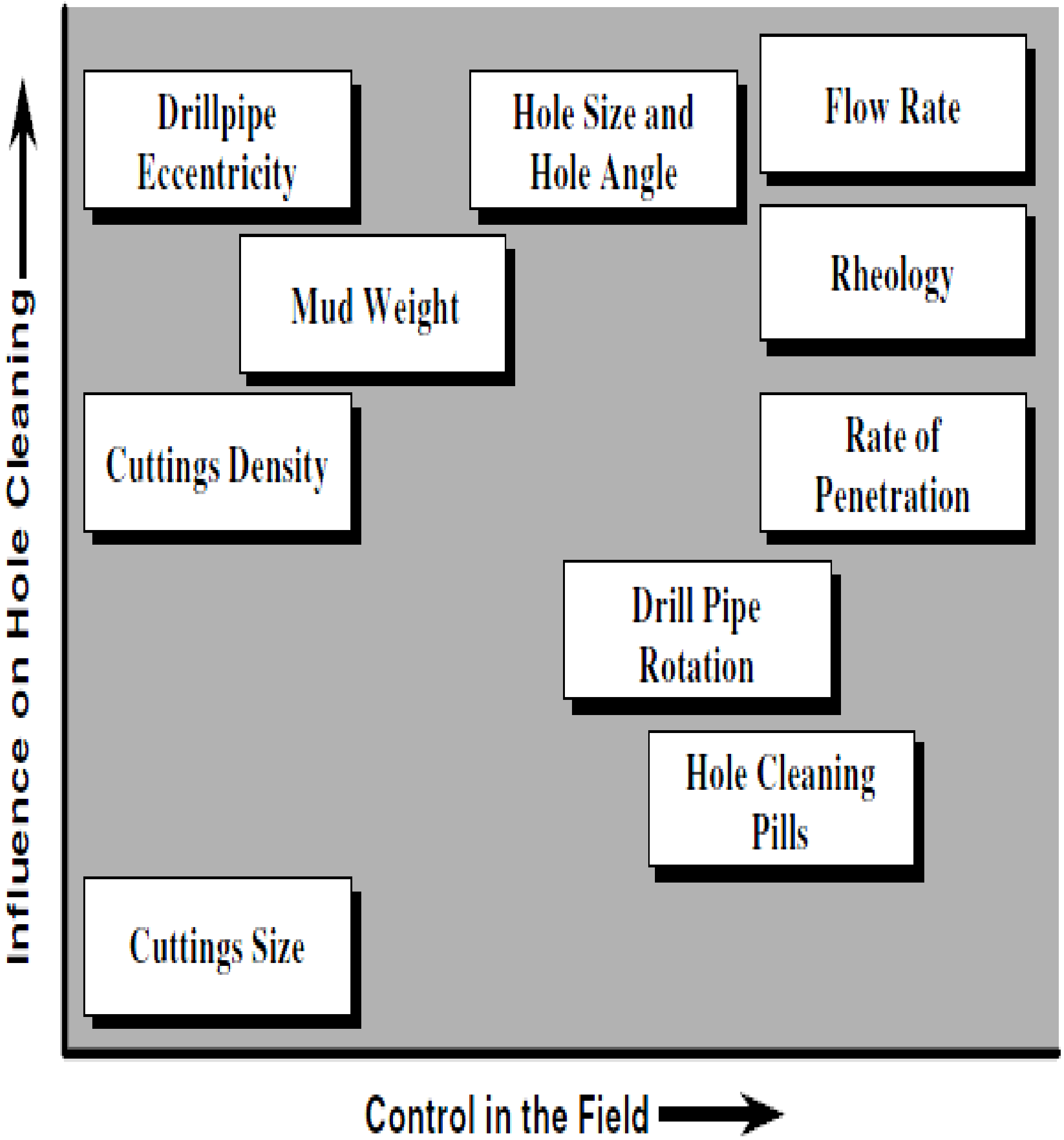

Figure 1.1: Drilling Parameters Affecting Cuttings Transport (Adari et al., 2000).

in a deviated well.

- To develop new equations governing the above parameters mentioned for Bingham plastic fluid in a deviated well using the work of Bourgoyne et al (1986) and Larsen et al (1997).
- To develop nomographs using a case study.
- To draw conclusions from the investigations carried out and make recommendations.

1.2 SCOPE OF WORK

The scope of this work is centered on the graphical evaluation of cuttings transport in Bingham plastic fluids. It expresses the relationships between annular velocity, transport ratio, flow rate, rate of penetration, hole size. The study is limited to highly deviated wells (55^o to 90^o). The equations developed are used to generate nomographs.

CHAPTER TWO

LITERATURE REVIEW

The transportation of cuttings and efficient hole cleaning are indispensible in any drilling program. This is because a successful drilling operation is the key to a profitable business in the oil and gas sector. These have driven researchers into the study of cuttings transport and hole cleaning so as to predict hole cleaning efficiency of drilling fluids and optimize a drilling program. Besides, these have helped to reduce the problems encountered during drilling operations and as such to reduce the cost of drilling. In the process, correlations and charts have been developed. These are either based on experiments termed as empirical approach or theoretical known as mechanistic approach. Below are some of the works that have been done in this area.

In 1951, Williams and Bruce deduced from their experiments that the carrying capacity of a drilling mud was increased when the mud weight increased and the viscosity was lowered. This was followed by Zeidler in 1972, through his experiments in which he concluded that increased particles transport was due to pipe rotation and turbulent stresses in fluid rather than to the flat velocity profiles in turbulent flow. Furthermore, Sifferman et al. (1974) conducted experiments to study the effects of various parameters on cuttings transport in full vertical annuli. They reported that the cuttings transport efficiency was controlled by annular velocity, rheological properties such as the fluid viscosity and density, cutting size, flow regime with little dependence on casing size, pipe rotation, drilling rate and drill pipe eccentricity.

Iyoho and Azar (1981) presented a new model for analytical solutions to the problems of non-Newtonian fluid flow through eccentric annuli. They concluded that, firstly, flow velocity was reduced in eccentric annulus. This 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 involved fluid flow through eccentric annuli.

Hussaini and Azar (1983) studied the behaviour of cuttings in a vertical annulus. They focused on 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. They also verified the Ziedler's transport model by using actual drilling fluids and found out that it was valid. 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.

Tomren et al. (1986) conducted an experimental study of cuttings transport in directional wells. A 40 ft pipe was used and several types of drilling fluids and different flow regimes were tested. The annulus angles varied from 0 ° to 90° and actual drill cuttings were used in the experiment. They performed a total of 242 different tests, varying angles of pipe inclination, pipe eccentricities, and different fluid flow regimes (laminar and turbulent). They discovered that the effective flow area was reduced by a growing formation cuttings bed at high liquids rates for angles that were greater than 40°. 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 concluded 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. They concluded that angles between 35° and 55° were critical angles since they caused bed forming and bed sliding downwards against the flow.

Okrajni and Azar (1986) did experiments on the effects 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° were identified. The observations showed that laminar flow was more effective in low angle wellbore (0° to 45°) 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°), turbulent and laminar flow had the same effect on the cuttings transport. The highest annular cuttings concentration was observed at critical angle of inclination, between 40° and 45°, 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 insignificant in the high inclination wellbore (55° to 90°). They recommended laminar flow for hole cleaning in interval 0° and 45°, and a turbulent flow for hole cleaning in interval 55 ° and 90°. 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.

Gavignet and Sobey (1989) presented a cuttings transport mechanistic model. They developed a two-layer model for cuttings transport in an eccentric annulus with a Non-Newtonian drilling fluid. They deduced the critical flow rate above which a bed would not form. 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 greater than 60°. They indicated that friction coefficient of the cuttings against the wall affected highly the bed formation at high angles of deviation. They compared their mechanistic model with the experimental results of Tomren et al. (1986) study.

Brown et al. (1989) 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 Hydroxyethylcellulose (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.

Ford et al. (1990) conducted an experimental study of drilled cuttings transport in inclined wellbore. During this research, two different cuttings transport mechanisms were presented: firstly, where the cuttings were transported to surface by a rolling or sliding motion along the lowest side of the annulus and secondly, 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 Minimum Transport Velocity (MTV), which was the minimum velocity needed to transport the cuttings up 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. They also observed that increasing viscosity of circulating fluid would lead to decreasing of MTV for cuttings both for rolling and in suspension form. The experiments indicated that in turbulent flow, water was a very effective transport fluid.

Peden et al. (1990) 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 the concept of MTV. The concept presumed that at lower MTV, a wellbore would be cleaned more effectively. They 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°, large cuttings were transported more effectively with high viscosity drilling fluid. Cuttings transport models were developed based on the forces acting on a cutting being transported upwards in a drilling fluid.

Becker et al. (1991) developed 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°, cuttings transport performance was more effective when drilling fluid was in the laminar flow regime. Furthermore, when wellbore inclinations were higher than 60° from vertical, cuttings transport performance was more effective when drillings fluid was in the 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. (1992) carried out 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.

Sifferman and Becker (1992) presented a paper in which 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 build-up. 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 accumulated easily in oil-based mud than in water-based mud.

In 1994, Luo et al. presented simple charts to determine hole cleaning requirements for a range of hole sizes. Furthermore, 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.

Belavadi and Chukwu (1994) 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. They deduced that increase in the fluid flow rate would increase cuttings transport performance in the annulus, when the drilling fluid density was 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.

Ford et al. (1996) introduced a computer package that could be used in the calculations of the MTV required to ensure effective hole cleaning in deviated wells. This computer program was developed based on extensive experimental 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, Hemphill and Larsen 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 the 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 these observations, it was stated that oil-based mud did not clean the wellbore as well 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.

Larsen et al. (1997) 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° 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 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 CTFV, SCFF, and CTV.

In 1997, Azar and Sanchez 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 exist, 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.

Kamp and Rivero (1999) 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. 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 developed an empirical model for estimating mud minimum velocity for cuttings transport in vertical and horizontal well. In his work, he modified Moore's 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 and Peden's experimental data to calculate the minimum transport velocity (Vmin). He 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.

Yu et al.(2004) 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 drill cuttings. This study proved that the method could improve stepwise cuttings transport capacity in horizontal and inclined wells.

Mirhaj et al. (2007) 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 variables 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 DRILLING FLUIDS RHEOLOGICAL MODELS

Fluids are generally categorized based on their flow behaviour when shear stresses are applied on them. Those that have the potential to recover fully or partially from their deformations (elasticity) once the shear stress on them are removed are called non-viscous fluid, examples of which are the visco-elastic fluids. Conversely, those that do not recover from the deformation caused by a shearing stress when the stress is removed are called viscous fluids. Viscous fluids are further classified into Newtonian and Non-Newtonian fluids based on their shear stress - shear rate relationships. These fluids are described with equations called their respective models. The diagrammatic classification of viscous fluids is shown in figure 2.1.

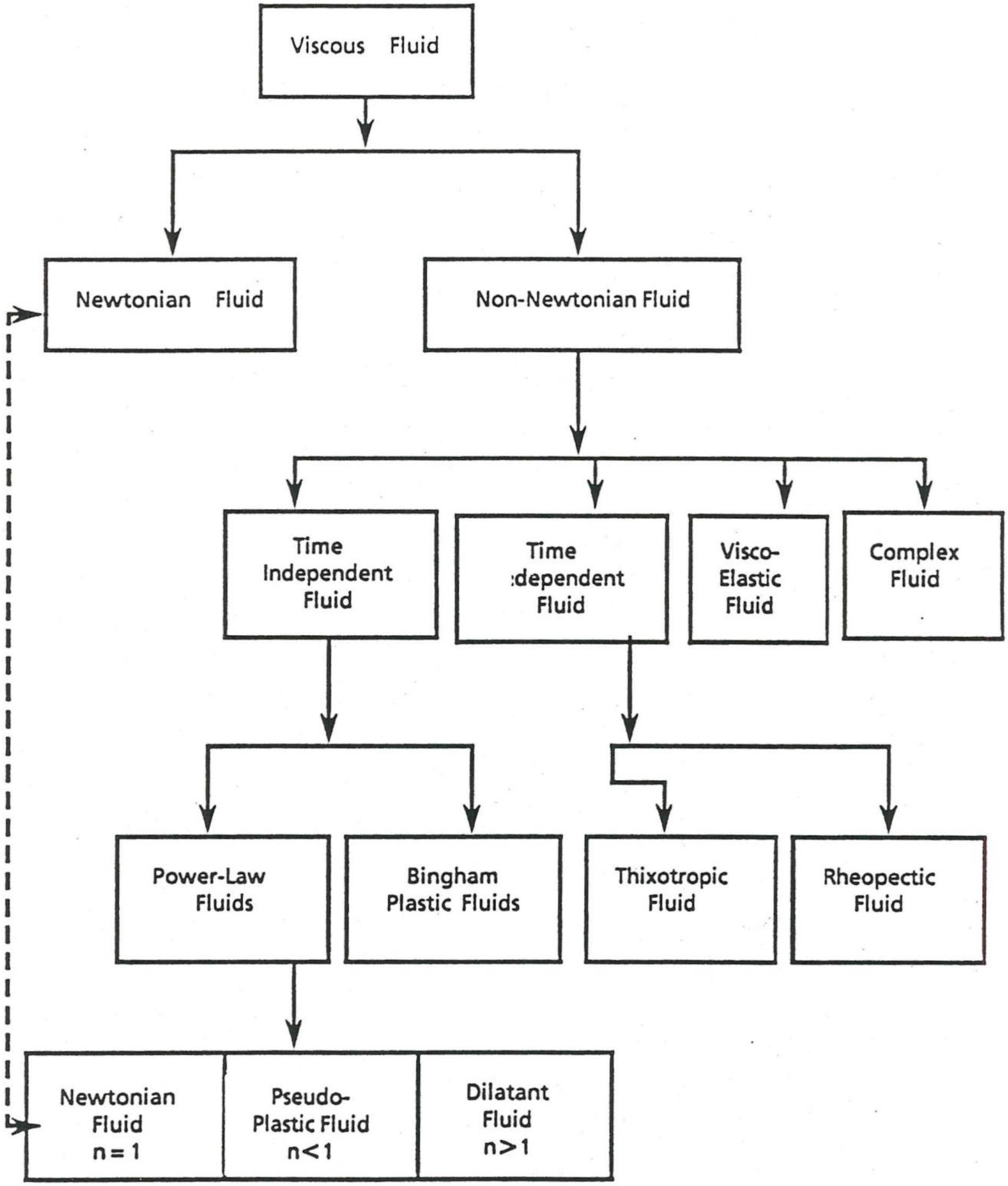

Figure 2.1: Classification of Viscous Fluids

2.1.1 Newtonian Fluids

These are fluid types, whose shear rate, γ, varies directly or linearly with the shear stress, τ. The constant of the direct proportionality is termed as the true or effective viscosity, μ, thus, the model is given as:

$$\tau = \mu\gamma \tag{2.1}$$

Where the shear rate is given by:

$$\gamma = \left(-\frac{dv}{dr}\right) \tag{2.2}$$

Graphically, the rheogram, which is a rate curve describing the relationship between shear stress and shear rate, of Newtonian fluids is shown in figure 2.2. Examples are water and kerosene.

2.1.2 Non-Newtonian Fluids

These are fluids which exhibit non-linear relationship between shear rate and shear stress causing the deformation and when they are proportional, their rheogram does not pass through the origin. There are many models used in describing different Non-Newtonian fluids, some of which are as follows:

- Power Law Model
- Bingham Plastic Model
- Herschel-Buckley Model
- Robertson-Stiff Model
- Casson Model

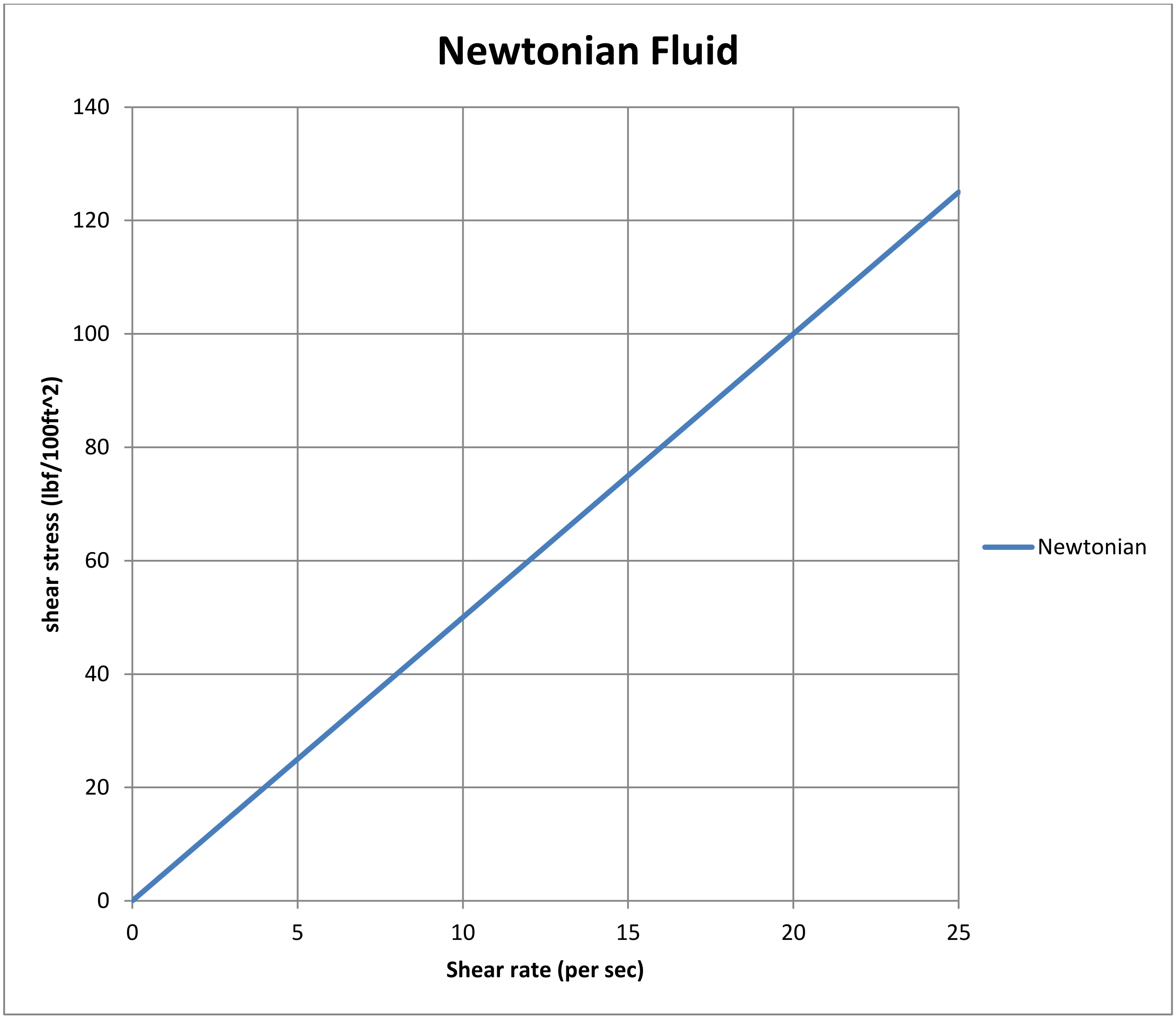

Figure 2.2: Shear rate – Shear stress relationship of Newtonian Fluids.

Power Law and Bingham Plastic models are most widely used in the industry as they approximate the behavior of most drilling fluids. This study is based on the cuttings transport with Bingham Plastic fluids.

2.1.2.1 Power Law Model

This model describes the behavior of fluids with non-linear proportionality relationship between shear stress and shear rate, and for which an infinitesimal shear stress will start motion. The equation for characterizing these fluids is shown in equation (2.3).

$$\tau = K\gamma^n \tag{2.3}$$

Where K is the consistency index factor, n, the flow behaviour index, τ, the shear stress and γ, the shear rate. The flow behaviour index n, is a measure of the deviation from the Newtonian law. Thus, for $n = 1$, implies Newtonian fluid. Values of $n < 1$, indicates Pseudo-plastic fluid (apparent viscosity decreases as shear rate increases) whereas $n > 1$, signifies dilatant fluid (apparent viscosity increases as shear rate increases). The consistency index factor K, is an indication of degree of solid concentration in the drilling fluid. The rheogram is presented in figure 2.3. Examples of Power Law fluids are polymeric solutions, clay, molasses, and paint.

2.1.2.2 Bingham Plastic Model

This model is used to characterize fluids which require a finite shearing stress to initiate motion and for which there is a linear relationship between the shearing stress in excess of the initiating stress and the resulting shear rate. The initiating stress is known as the yield stress (or yield point). This is a two-parameter model involving the yield point (τ_0) and plastic viscosity (μ_p) that is independent of shear rate. The constitutive equation is as represented in equation 2.4.

$$\tau = \tau_0 + \mu_p \gamma \tag{2.4}$$

Where τ = shear stress, τ_0= yield stress, μ_p= plastic viscosity, γ= shear rate. The slope of the line is the plastic viscosity and the intercept is the yield stress or commonly known as yield point.

The rheogram is also presented in figure 2.3. Examples of fluids include: clay, mud, ketchup and chewing gum.

2.1.2.3 Herschel-Buckley Model

This model represents fluids which combine the behavior of Bingham plastic fluid and that of Pseudo-plastic form of Power law fluid. They are characterized by a combined form of the models of Bingham plastic and Power law models as shown in equation 2.5.

$$\tau = \tau_0 + K\gamma^n \tag{2.5}$$

Thus, for $\tau_0 = 0$, implies Herschel-Buckley approximates power law while for $n = 1$ signifies Bingham plastic model with $K = \mu_p$, and $\tau_0 = 0$ and $n = 1$ indicate Newtonian fluid.

2.1.2.4 Robertson-Stiff Model

Robertson-Stiff model is used for characterizing non Newtonian fluids that possess a yield value. It is also a combination of Bingham plastic and pseudoplastic power law models. It is a three-parameter model represented as shown in equation 2.5.

$$\tau = K[\gamma + C]^n \qquad , \qquad \tau > \tau_0 = KC^n \tag{2.6}$$

Where τ is shear stress, τ_0 is the Robertson-Stiff yield stress, γ is the shear rate of strain, n is the flow behaviour index, K and C are consistency and the material constant respectively. When τ_0 is exceeded, pseudo-plastic flow is initiated with the fluid flowing as if the stress causing the flow is less than the minimum fluid stress.

2.1.2.5 Casson Model

Casson model was originally introduced for the prediction of flow behaviour of pigment-oil suspensions. It is based on a structure model of the interactive behaviour of solid and liquid phases of a two-phase suspension (Casson, 1959). According to Cho and Kensey (1994), the model describes the flow of visco-plastic fluids that is represented by equations (2.7) and (2.8).

$$\sqrt{\tau} = \sqrt{\tau_y} + \sqrt{(k\gamma)} \quad when \ , \ \tau \geq \tau_y \tag{2.7}$$

$$\gamma = 0 \quad when \ \ \tau \leq \tau_y \tag{2.8}$$

Where k is a Casson model constant.

The Casson model shows both yield stress and shear thinning Non-Newtonian viscosity. For materials such as blood and food products, it provides better fit than the Bingham plastic model.

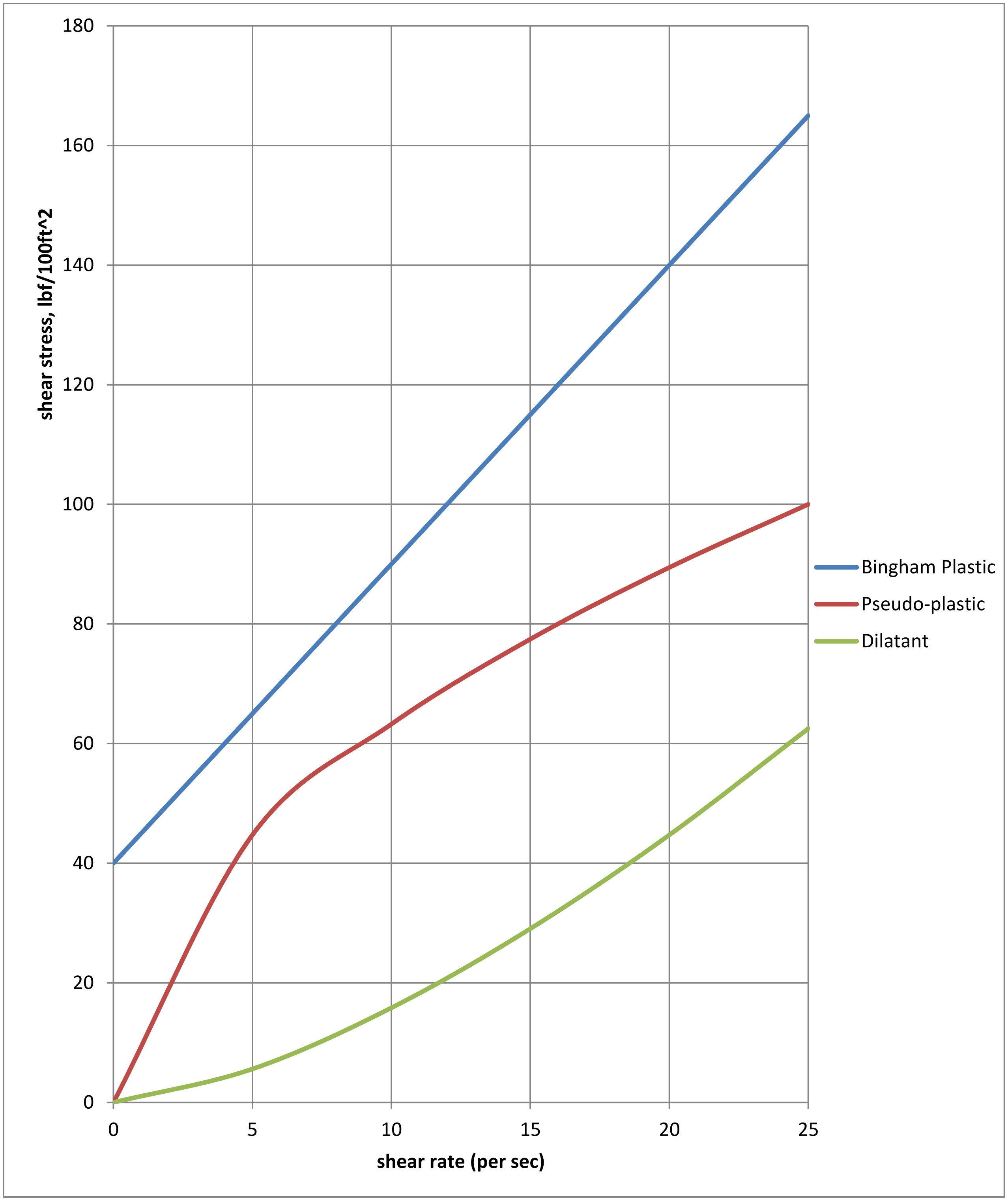

Figure 2.3: Shear Rate – Shear Stress Relationship for Power law and Bingham Plastic Fluids

CHAPTER THREE

DEVELOPMENT OF EQUATIONS

3.1 ASSUMPTIONS

1. The derivations performed were based on the definition of the Critical Transport Fluid Velocity (CTFV), that is, subcritical fluid flow was not considered.
2. Slip velocity effect is factored in, in the expression for cuttings concentration.

3.2 ANNULAR VELOCITY AND TRANSPORT RATIO

According to Bourgoyne et al. (1986), the volume fraction of cuttings in the mud can be determined by considering the feed rate, q_s of cuttings at the bit, and the cuttings transport ratio, F_T. Thus, mathematically:

$$\bar{v}_T = \frac{q_s}{A_a f_s} \tag{3.1}$$

and

$$\bar{v}_a = \frac{q_m}{A_a(1 - f_s)} \tag{3.2}$$

Where v_T is the transport velocity of the cuttings, v_a, the fluid velocity, A_a, the borehole annulus area, q_m, the mud flow rate and f_s , the volume fraction of cuttings in the mud.

Expressing f_s in percentages and substituting in equation (3.2), gives:

$$\bar{v}_a = \frac{100q_m}{A_a(100 - f_{sp})} \tag{3.3}$$

Using Bingham plastic fluids in highly deviated wells (55^0 to 90^0)., Larsen et al. (1997) showed from their experiments that:

$$f_{sp} = 0.01778R_p + 0.505 \tag{3.4}$$

Where R_p is the rate of penetration (ROP) in ft/hr. Substituting equation (3.4) into equation (3.3) and simplifying, results to:

$$\bar{v}_a = \frac{100q_m}{A_a(99.5 - 0.01778R_p)} \tag{3.5}$$

but $$A_a = A_{hole} - A_{pipe} \tag{3.6}$$

$$A_a = A_{hole}\left(1 - \frac{A_{pipe}}{A_{hole}}\right) \tag{3.7a}$$

$$A_a = A_{hole}\left[1 - \left(\frac{D_{pipe}}{D_{hole}}\right)^2\right] \tag{3.7b}$$

Substituting equation (3.6) into (3.3) gives

$$\bar{v}_a = \frac{100q_m}{(A_{hole} - A_{pipe})(99.5 - 0.01778R_p)} \tag{3.8}$$

or $$\bar{v}_a = \frac{400q_m}{\pi({D^2}_{hole} - {D^2}_{pipe})(99.5 - 0.01778R_p)} \tag{3.9a}$$

and $$\bar{v}_a = \frac{127.324q_m}{({D^2}_{hole} - {D^2}_{pipe})(99.5 - 0.01778R_p)} \tag{3.9b}$$

Converting q_m to field unit and diameter in inches gives:

$$\boldsymbol{\bar{v}_a = \frac{40.8528 q_m}{\left({D^2}_{hole} - {D^2}_{pipe}\right)\left(99.5 - 0.01778 R_p\right)}} \qquad \mathbf{(3.10)}$$

Solving for $\boldsymbol{q_m}$ gives

$$\boldsymbol{q_m = \frac{1}{40.8528}\left[\bar{v}_a\left({D^2}_{hole} - {D^2}_{pipe}\right)\left(99.5 - 0.01778 R_p\right)\right]} \qquad \mathbf{(3.11)}$$

Where $\bar{v}_a$is in $ft/s,\ R_p$ is in ft/hr, q_m in gal/min, D_{hole} and D_{pipe} in $inches$.

Cuttings transport ratio, F_T is given by

$$F_T = \frac{\bar{v}_T}{\bar{v}_a} = \frac{\frac{q_s}{A_a f_s}}{\frac{q_m}{A_a(1 - f_s)}} \qquad (3.12)$$

$$F_T = \frac{q_s}{q_m}\left(\frac{1 - f_s}{f_s}\right) \qquad (3.13)$$

$$and \qquad f_s = \frac{q_s}{q_s + F_T q_m} \qquad (3.14)$$

Converting f_s to f_{sp} and equating to equation (3.4) leads to equation (3.15)

$$f_{sp} = 100 f_s = \frac{100 q_s}{q_s + F_T q_m} = 0.01778 R_p + 0.505 \qquad (3.15)$$

But cuttings flow rate , q_s, can be expressed in terms of rate of penetration as:

$$q_s = \frac{R_p A_{hole}}{3600} \qquad (3.16)$$

where $R_p$is in ft/hr, A_{hole} in ft^2 and $q_s$in ft^3/s

Substituting equation (3.16) for q_s into 3.11 and from equation (3.2) for q_m gives

$$F_T = \frac{R_p A_{hole}}{3600 A_a \bar{v}_a f_s} \tag{3.17}$$

Converting f_s to $f_{sp}$and substituting equations (3.4) and (3.7b) into (3.15)

$$F_T = \frac{R_p}{36\bar{v}_a \left[1 - \left(\frac{D_{pipe}}{D_{hole}}\right)^2\right](0.01778R_p + 0.505\ )} \tag{3.18}$$

Substituting for $\bar{v}_a$from equation (3.10) into equation (3.18) gives

$$F_T = \frac{\left(99.5 - 0.01778R_p\right)R_p {D^2}_{hole}}{1470.7008q_m\left(0.01778R_p + 0.505\ \right)} \tag{3.19}$$

$$\boldsymbol{F_T = \frac{\left(99.5 - 0.01778R_p\right){D^2}_{hole}}{q_m\left(26.149 + \frac{742.7}{R_p}\right)}} \tag{3.20}$$

Where R_p is inft/hr, q_m in gal/min and D_{hole} in $inches$.

In terms of annular clearance, from equation (3.10):

$$\bar{v}_a = \frac{40.8528q_m}{\left({D^2}_{hole} - {D^2}_{pipe}\right)\left(99.5 - 0.01778R_p\right)} \tag{3.10}$$

$$\bar{v}_a = \frac{40.8528q_m}{\left(D_{hole} + D_{pipe}\right)\left(99.5 - 0.01778R_p\right)\left(D_{hole} - D_{pipe}\right)} \tag{3.21}$$

But $$A_{cl} = D_{hole} - D_{pipe} \tag{3.22}$$

$$D_{hole} = A_{cl} + D_{pipe} \tag{3.23}$$

Where A_{cl} is the annular clearance in inches

Substituting equation (3.19) and (3.20) in equation (3.18)

$$\bar{v}_a = \frac{40.8528q_m}{\left(D_{hole} + D_{pipe}\right)\left(99.5 - 0.01778R_p\right)\ A_{cl}} \tag{3.24}$$

Substituting equation (3.22) in (3.20)

$$\boldsymbol{\bar{v}_a = \frac{40.8528q_m}{\left(99.5 - 0.01778R_p\right)\left(2D_{pipe}+A_{cl}\right)A_{cl}}} \tag{3.25}$$

Similarly

$$F_T = \frac{\left(99.5 - 0.01778R_p\right)D^2{}_{hole}}{q_m\left(26.149 + \frac{742.7}{R_p}\right)} \tag{3.20}$$

Substituting equation (3.22) into equation (3.20)

$$\boldsymbol{F_T = \frac{\left(99.5 - 0.01778R_p\right)(\ D_{pipe} + A_{cl})^2}{q_m\left(26.149 + \frac{742.7}{R_p}\right)}} \tag{3.26}$$

3.3 EFFECTIVE ANNULAR MUD DENSITY

According to Bourgoyne et al. (1986), the effective annular mud density $\bar{\rho}$, can be determined from equation (3.27).

$$\bar{\rho} = \rho_m(1 - f_s) + \rho_s f_s \tag{3.27}$$

Converting f_s to percentage and substituting equation (3.4)

$$\boldsymbol{\bar{\rho} = \frac{1}{100}\left[0.505\rho_s + 99.5\rho_m + 0.01778(\rho_s - \rho_m)R_p\right]} \tag{3.28}$$

CHAPTER FOUR

DEVELOPMENT OF NOMOGRAPHS

4.1 CASE STUDY ON ANNULAR VELOCITY AND TRANSPORT RATIO

The iterative method of calculating slip velocity proposed by Larsen et al. (1997) is used in developing graphs of transport ratio, annular velocity and mud flow rates against annular clearances for various hole inclinations. The parameters used are shown in table 4.1.

The data obtained from the Matlab codes in Appendix A are tabulated in Appendix B and the graphs plotted are shown in figures 4.1, 4.2 and 4.3. Besides, the new equation (3.25) is used in developing a nomograph of figure 4.4 from the values in Appendix C.

4.1.1 Sample Calculations

With the drilling parameters in Table 4.1, the calculations made were tabulated as shown in table 4.2. Using the Larsen et al. (1997) method, for an annular clearance of 5 inches and a hole angle of 55^o, the annular velocity is 4.33 ft/s (figure 4.1) for a flow rate of 516.91 gal/min and a transport ration of 0.26. Alternatively, a similar flow rate of 509.32 gal/min is obtained with the new equation (3.25) or figure 4.4, for an annular velocity of 4.33 ft/s. In addition, the transport ratio is calculated with equation (3.26) as:

$$F_T = \frac{(99.5 - 0.01778\ x33)(2.375 + 5)^2}{509.32\left(26.149 + \frac{742.7}{54}\right)} \tag{3.26}$$

$$= 0.30$$

Similarly, with the Larsen et al. (1997) method, for an annular clearance of 3 inches and a hole angle of 75°, the annular velocity is 4.63 ft/s (figure 4.1) for a flow rate of 263.61 gal/min and a transport ration of 0.27. Alternatively, a similar flow rate of 259.74 gal/min is obtained from the new equation (3.25) or from figure 4.4, for an annular velocity of 4.63 ft/s. In addition, the transport ratio is calculated with equation (3.26) as:

$$F_T = \frac{(99.5 - 0.01778\ x54)(2.375 + 3)^2}{259.74\left(26.149 + \frac{742.7}{54}\right)} \tag{3.26}$$

$$= 0.27$$

It should be noted that the new set of equations predicts the same cleaning efficiency (Transport Ratio) as the Larsen et al., (1997) method with lower flow rates (509.32 and 259.74) compared to that of Larsen et al., (1997) method (516.91 and 263.61) respectively. This is because the new equation (equation 3.25) incorporates the cutting concentration in the calculation for mud flow rate. This reduces the quantity of mud consumed and thus, saving cost.

4.2 MEAN MUD DENSITY

Equation (3.28) is used to plot the graph in figure 4.5 from the data in Appendix D. The figure shows a linear relationship between ROP and mean mud density.

TABLE 4.1: Drilling Operation Parameters for the Case Study

Parameters	Values
Drill Pipe Diameter, inches	2.375
Rate of Penetration, ft/hr	54
Mud weight, lbm/ gal	11
Plastic Viscosity, cp	7
Yield Point, lbf/100ft^2	7
Cuttings size, inches	0.175 (medium)

TABLE 4.2: Comparative Results of the Sample Calculations

Parameters	**Larsen et al.(1997) Method**	**New Equations**	**Larsen et al. (1997) Method**	**New Equations**
Hole Angle	55		75	
Annular Clearance (in)	5	5	3	3
Annular Vel (ft/s)	4.33	4.33	4.63	4.63
Mud Flow Rate (gal/min)	516.91	509.32	263.61	259.74
Transport Ratio	0.26	0.26	0.27	0.27

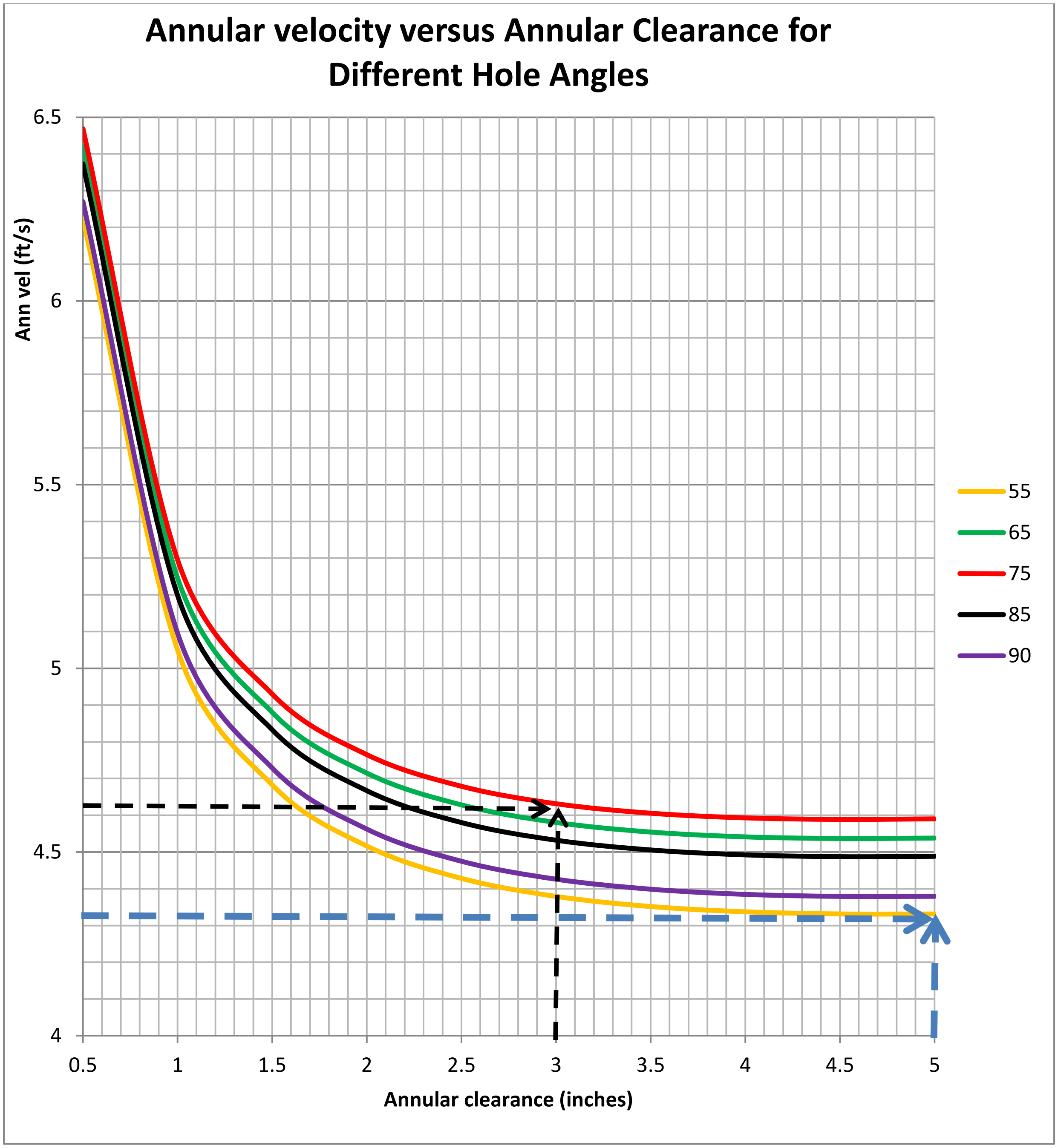

Figure 4.1: Annular Velocity versus Annular Clearance for Different Hole Angles

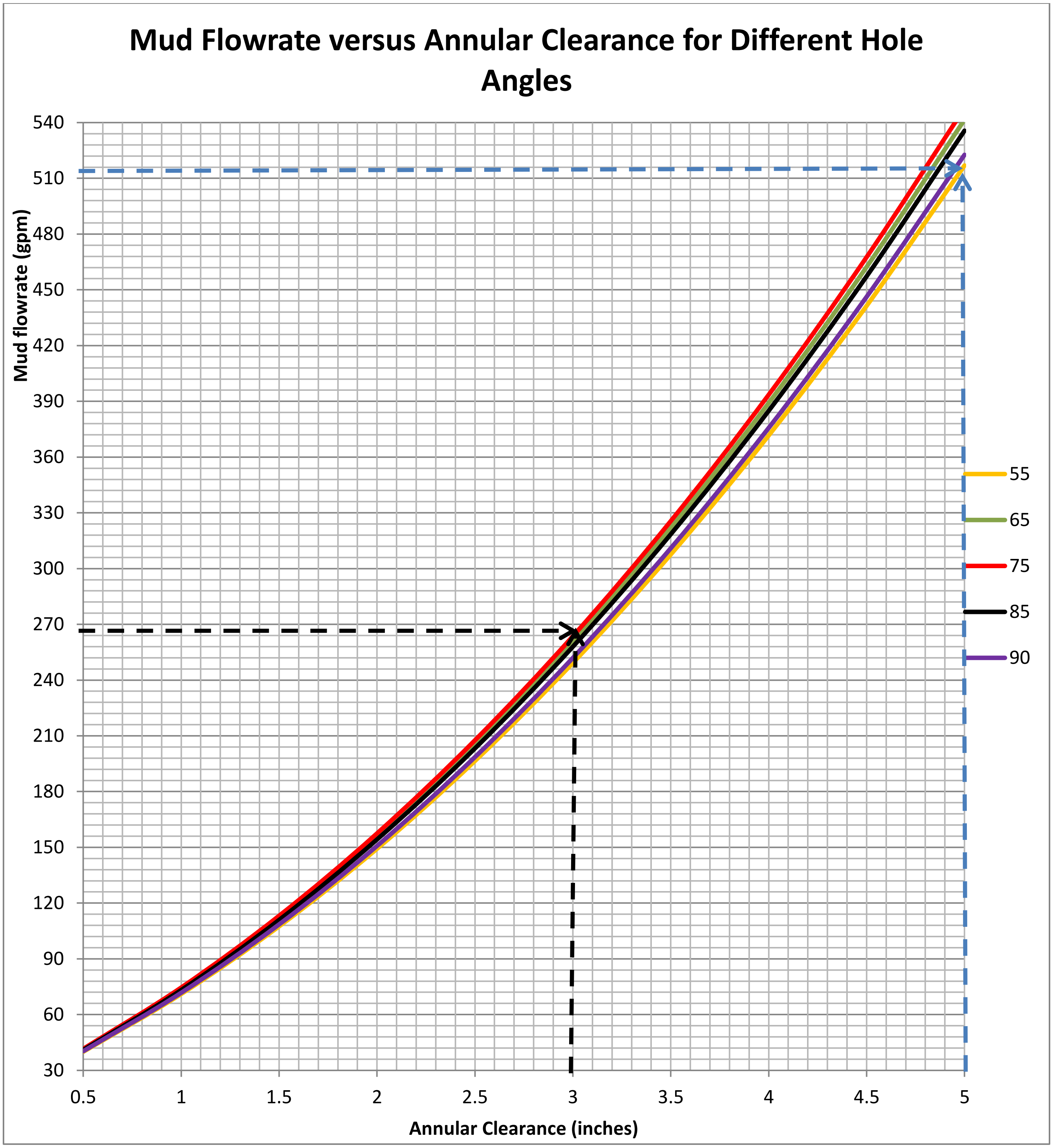

Figure 4.2: Mud Flow rate versus Annular Clearance for Different Hole Angles

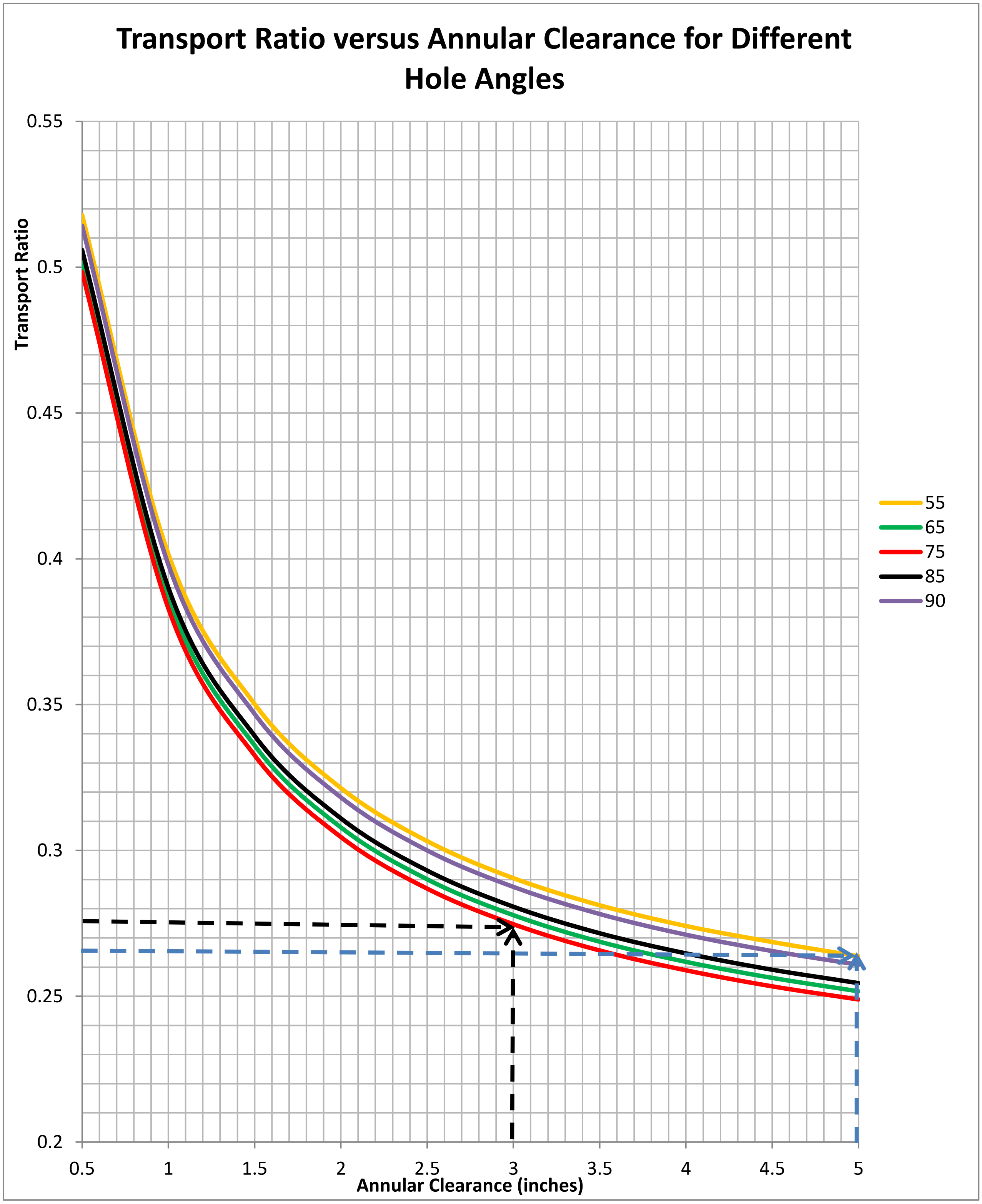

Figure 4.3: Transport Ratio versus Annular Clearance for Different Hole Angles

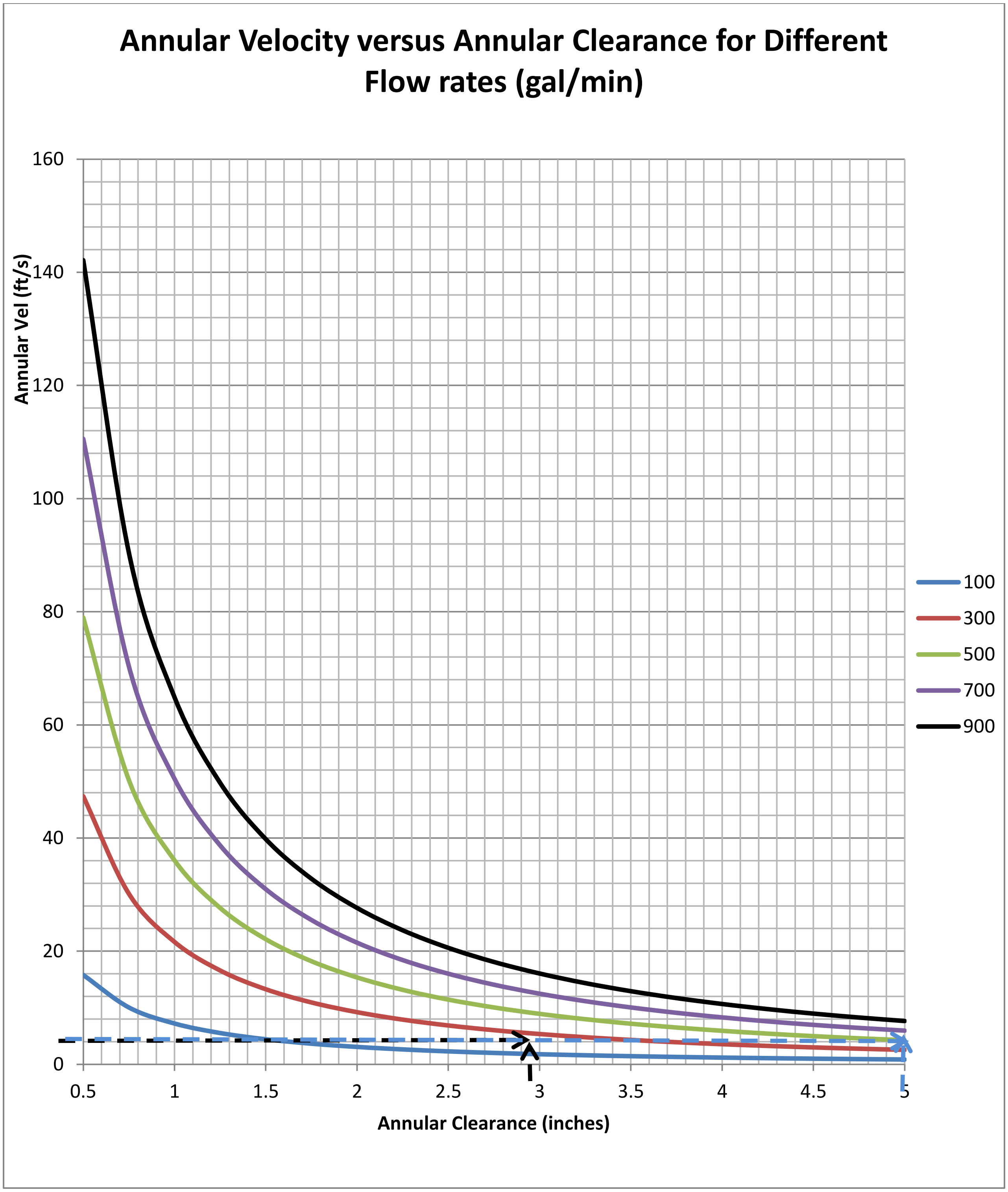

Figure 4.4: Nomograph of Annular Velocity versus Annular Clearance for Different Flow rates for the Case Study

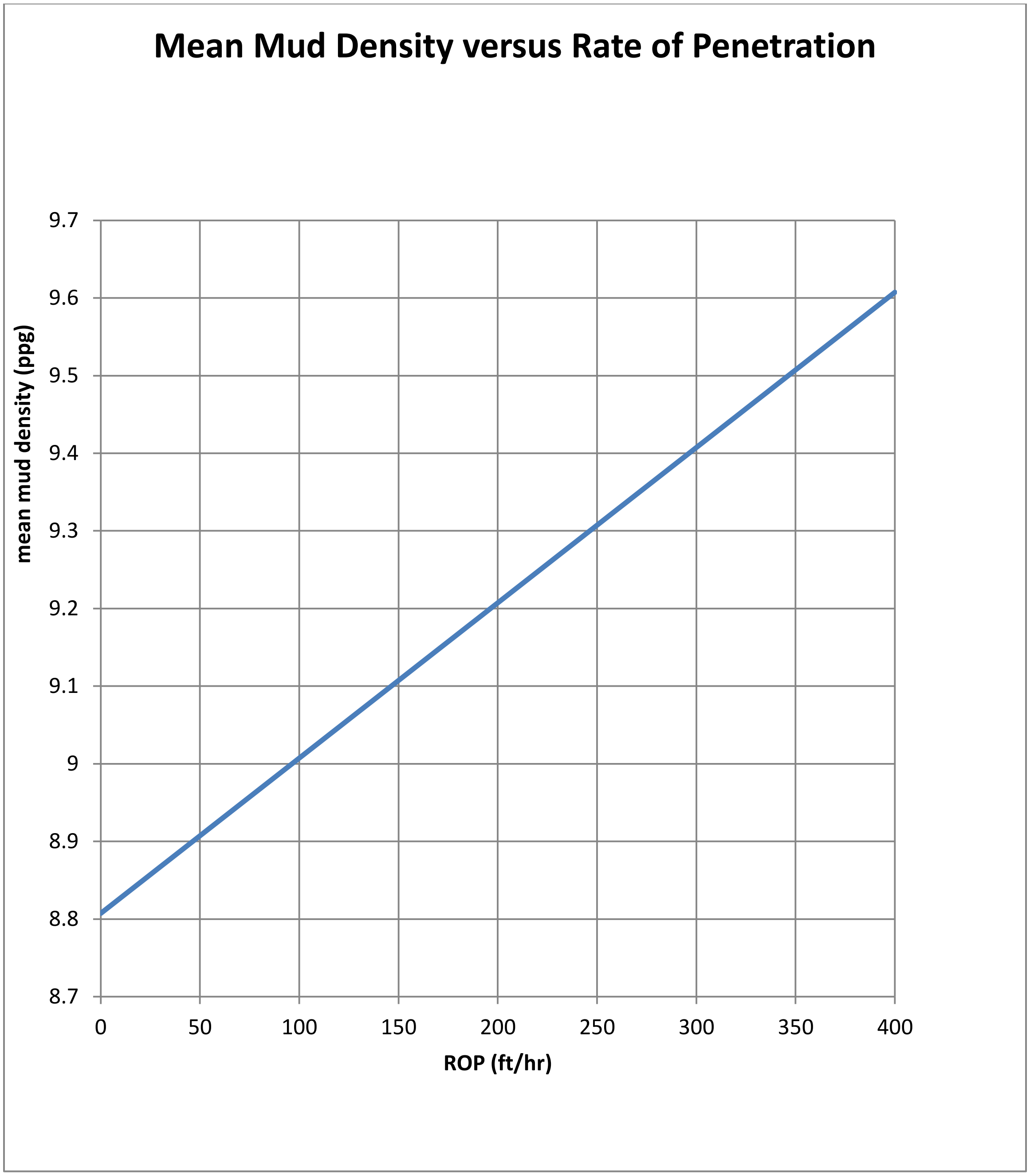

Figure 4.5: Graph of Mean Mud Density against Rate of Penetration

4.3 VALIDATION WITH AN EXAMPLE WELL DATA

The equations developed are validated with the data from an example well used in the work of Ranjbar (2010). The data typify a practical drilling situation with the well comprising of both vertical and horizontal sections. The horizontal section is deviated up to an angle of 90°. It is customary, in practice, to drill this deviated section with flow rates in the range of 1500 to 2000 l/min. The drilling parameters are shown in table 4.3.

The results obtained from the Larsen et al. (1997) method and that of the new equations are shown in table 4.4. Using the Larsen et al. (1997) method, for an inclination of 65°, the annular velocity is 4.24 ft/s with a mud flow rate of 490.26 (1855.84 l/min) and a transport ratio of 0.30. With the new equation (3.25), a nomograph is plotted using the data in Appendix E as presented in figure 4.6. An annular velocity of 4.24 ft/s gives a mud flow rate of 485.07 gpm (1836.19 l/min). In addition, the transport ratio is calculated from equation 3.26 as:

$$F_T = \frac{(99.5 - 0.01778\, x33)(5 + 3.5)^2}{485.07\left(26.149 + \frac{742.7}{33}\right)} \tag{3.26}$$

$$= 0.30$$

Similarly, for an inclination of 90°, the annular velocity is 4.20 ft/s with a mud flow rate of 474.31 gal/min (1795.46 l/min) and a transport ratio of 0.31. With the new equation (3.25), an annular velocity of 4.10 ft/s gives a mud flow rate of 469.05 gal/min (1775.55 l/min). In addition, the transport ratio is calculated from equation 3.26 as:

$$F_T = \frac{(99.5 - 0.01778\, x 33)(5 + 3.5)^2}{469.05\left(26.149 + \frac{742.7}{33}\right)} \tag{3.26}$$

$$= 0.31$$

Besides, the mud density is predicted using equation (3.28):

$$\bar{\rho} = \frac{1}{100}\left[0.505\rho_s + 99.5\rho_m + 0.01778(\rho_s - \rho_m)R_p\right] \tag{3.28}$$

Substituting

$$\bar{\rho} = \frac{1}{100}[0.505\ x\ 19 + 99.5\ x\ 10.83 + 0.01778(19 - 10.83)33]$$

$$\bar{\rho} = 10.92\ lb/gal$$

4.4 STEPS IN USING THE NEW EQUATIONS

1. The mud flow rate is determined from the fluid transport velocity from equation 3.25. In practice, according to Tomren et al. (1986), fluid transport velocities of between 4 ft/s and 5 ft/s are typically used for common drilling muds.
2. The corresponding transport ratio is calculated from equation (3.26) using the mud flow rate from equation (3.25).
3. The mean mud density is obtained from equation (3.28).

TABLE 4.3: Drilling Operation Parameters for an Example Well

Parameters	Values
Drill Pipe Diameter, inches	5
Hole Diameter, inches	8.5
Rate of Penetration, ft/hr	33
Mud weight, lbm/ gal	10.83
Plastic Viscosity, cp	7
Yield Point, lbf/100ft^2	7
Cuttings size, inches	0.3
Cuttings density, lbm/gal	19
Revolution Per Minute	80

TABLE 4.4: Comparative Results of the Example Well Data

Parameters	**Larsen et al.(1997) Method**	**New Equations**	**Larsen et al. (1997) Method**	**New Equations**
Hole Angle	65	-	90	-
Annular Clearance (in)	3.5	3.5	3.5	3.5
Annular Vel (ft/s)	4.24	4.24	4.10	4.10
Mud Flow Rate (gal/min)	490.26 (1855.84 l/min)	485.07 (1836.19 l/min)	474.31 (1795.46 l/min)	469.05 (1775.55 l/min)
Transport Ratio	0.30	0.30	0.31	0.31
Mean Mud Density (ppg)	-	10.92	-	10.92

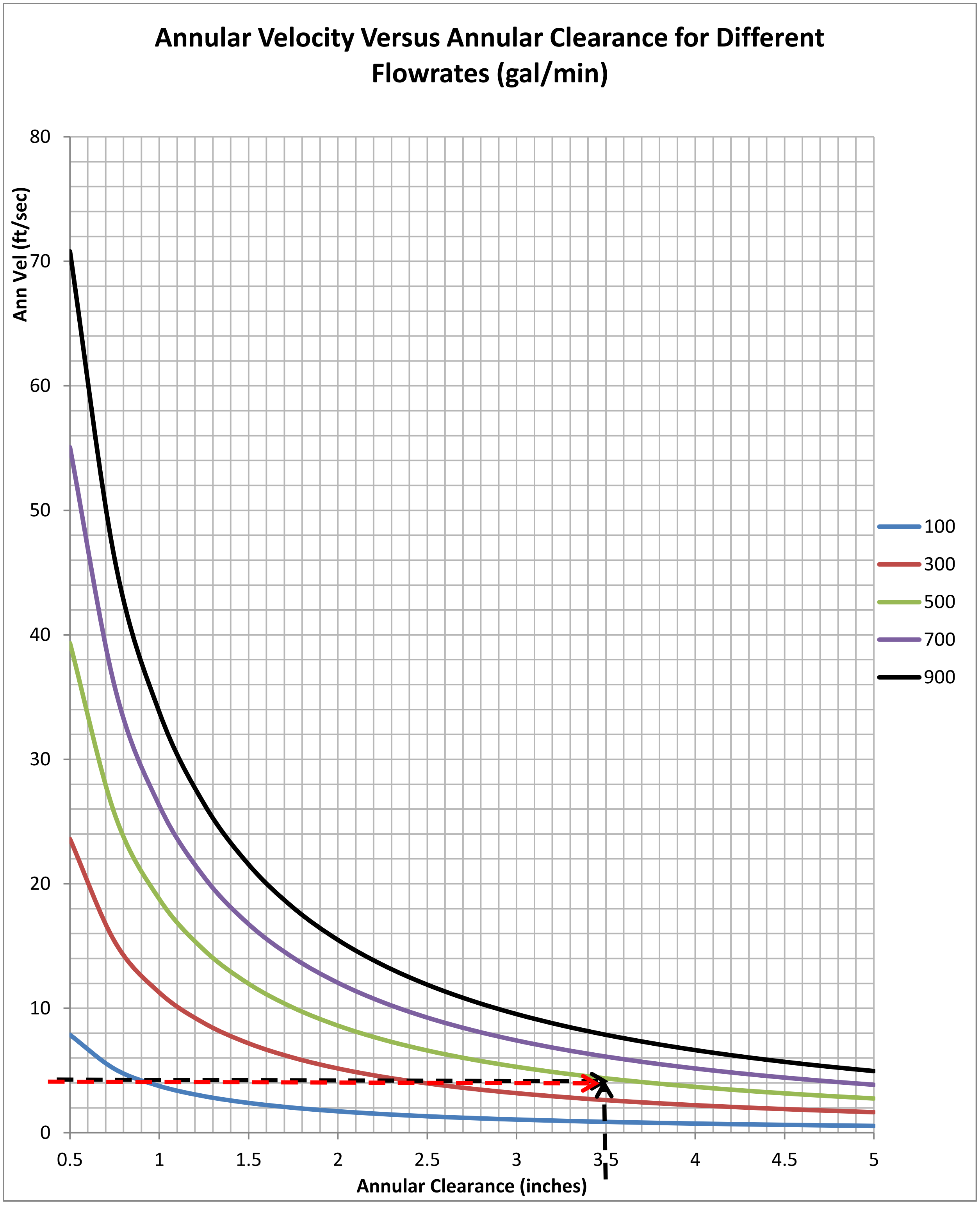

Figure 4.6: Nomograph of Annular Velocity versus Annular Clearance for Different Flow rates for the Example Well Data in Appendix E.

4.5 ADVANTAGES OF THE NEW EQUATIONS

1. It eliminates the rigor involved in the iterative method of Larsen et al (1997) in determining slip velocity.
2. The prediction is independent of the fluid rheology, mud density, hole angle and the cuttings density. (equation 3.25)
3. The results obtained are very close to those obtained using Larsen et al. (1997) method.
4. It is very simple to use as the equations are not complex.
5. It predicts in addition, the mean mud density (equation 3.28).

4.6 LIMITATION OF THE NEW EQUATIONS

1. It cannot predict correctly the parameters for other angles below 55^{o}
2. It cannot be used for other types of fluids (Power law fluids, Herschel-Buckley fluids etc.)

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

1 The iterative method of calculating minimum transport velocity was extended to determine critical transport flow rate and associated transport ratio for angles between 55^o to 90^o

2 These were used to develop nomographs of annular velocity, mud flow rate and transport ratio with annular clearance for different hole angles.

3 New equations were developed which predicted correctly the mud flow rate, annular velocity, annular clearance and transport ratio as well as the mean mud density when compared to the method by Larsen et al (1997). These models were developed for Bingham plastic fluids in highly deviated wellbores.

5.2 RECOMMENDATIONS

1. Similar work should be done for Power law fluids as well as other types of fluids.
2. The models should be extended to all hole angles, ranging from vertical, near vertical, highly deviated to horizontal wellbores.

NOMENCLATURE

F_T	Transport Ratio
$\bar{v}_T$	Cuttings Transport Velocity, ft/s
$\bar{v}_a$	Annular Mud Velocity, ft/s
$\bar{v}_{sl}$	Cuttings Slip Velocity, ft/s
YP	Yield Point, lbf/100ft^2
PV	Plastic Viscosity, cp
MTV	Minimum Transport Velocity, ft/s
ROP	Rate of Penetration, ft/hr
RPM	Revolution Per Minute
CTFV	Critical Transport Fluid Velocity, ft/s
CTV	Cuttings Transport Velocity, ft/s
SCFF	Subcritical Fluid Flow
Vmin	Minimum Transport Velocity, ft/s
τ	Shear Stress, lbf/100ft^2
μ	Dynamic Viscosity, cp
γ	Shear Rate, per sec
$\left(-\frac{dv}{dr}\right)$	Velocity Gradient, per sec
n	Flow Behaviour Index
τ_0	Yield Point, lbf/100ft^2
μ_p	Plastic Viscosity, cp
C	Material Constant, per sec

τ_y	Shear Stress, lbf/100ft^2
q_s	Cutiings Flow Rate, gal/min
q_m	Mud Flow Rate, gal/min
A_a	Annular Area, inch^2
f_s	Annular Cuttings Concentration by Volume, fraction
f_{sp}	Annular Cuttings Concentration by Volume, percentage (%)
R_p	Rate of Penetration, ft/hr
A_{hole}	Hole Cross Sectional Area, inch^2
A_{pipe}	Drill Pipe Cross Sectional Area, inch^2
D_{pipe}	Drill Pipe Diameter, inches
D_{hole}	Hole Diameter, inches
A_{cl}	Annular Clearance, inches
$\bar{\rho}$	Mean Mud Density, lb/gal
ρ_m	Mud Density, lb/gal
ρ_s	Cuttings Density, lb/gal

REFERENCES

1. Peden, J.M., Ford, J.T., and Oyeneyin, M.B.: "Comprehensive Experimental Investigation of Drilled Cuttings Transport in Inclined Wells Including the Effects of Rotation and Eccentricity," paper SPE 20925 presented at Europec 1990, The Hague, Netherlands, October 22-24 (1990)
2. Larsen, T.I., Pilehvari, A.A., and Azar, J.J.: "Development of a New Cuttings-Transport Model for High-Angle Wellbores Including Horizontal Wells," paper SPE 25872 presented at the 1993 SPE Annual Technical Conference and Exhibition, Denver, April 12 – 14, 1993. Also SPE Drilling and Completion Journal Paper, June 1997, pp. 129 – 135 (1997)
3. Rudi Rubiandini, R.S.: "Equation for Estimating Mud Minimum Rate for Cuttings Transport in an Inclined-Until-Horizontal Well", paper SPE/IADC 57541 presented at the 1999 SPE Annual Technical Conference and Exhibition, Abu Dhabi, November 8- 10 (1999)
4. Moore, Preston L.: "Drilling Practice Manual," The Petroleum Publishing Co., Tulsa, (1974)
5. Iyoho, A.W. and Azar, J.J.:"An Accurate Slot-Flow Model for Non-Newtonian Fluid Flow Through Eccentric Annuli," paper SPE 9447 presented at the 55th Annual Technical Conference and Exhibition, Dallas, September 21-24 (1981)
6. Hussaini, S.M. and Azar, J.J.:"Experimental Study of Drilled Cuttings Transport Using Common Drilling Muds," SPEJ, (February 1983), pp. 11-20
7. Tomren, P.H., Iyoho, A.W., and Azar, J.J.:"Experimental Study of Cuttings Transport in Directional Wells," SPEDE (February 1986), pp. 43-56.

8. Okrajni, S.S. and Azar, J.J.: "The Effects of Mud Rheology on Annular Hole Cleaning in Directional Wells," SPEDE (August 1986), pp. 297-308.

9. Brown, N.P., Bern, P.A. and Weaver, A.: "Cleaning Deviated Holes: New Experimental and Theoretical Studies," paper SPE/IADC 18636 presented at the 1989 SPE/IADC Drilling Conference, New Orleans, February 28–March 3 (1989)

10. Ford, J.T., Peden, J.M., Oyeneyin, M.B., and Zarrough, R.: "Experimental Investigation of Drilled Cuttings Transport in Inclined Boreholes," paper SPE 20421 presented at the 65th Annual Technical Conference and Exhibition, New Orleans, September 23-26 (1990)

11. Becker, T.E., Azar, J.J., and Okrajni, S.S.: "Correlations of Mud Rheological Properties With Cuttings-Transport Performance in Directional Drilling," SPEDE (March 1991), pp. 16 – 24.

12. Luo, Y., Bern, P.A. and Chambers, B.D.: "Flow-Rate Prediction for Cleaning Deviated Wells," paper SPE/ IADC 23884 presented at the 1992 IADC / SPE Drilling Conference, New Orleans, February 18-21, pp. 367-376 (1992)

13. Sifferman, T.R. and Becker, T.E.: "Hole Cleaning in Full-Scale Inclined Wellbores," SPEDE (June 1992), pp. 115-120.

14. Luo, Y., Bern, P.A., Chambers, B.D., and Kellingray, D.S.: "Simple Charts To Determine Hole Cleaning Requirements in Deviated Wells," paper IADC/SPE 27486 presented at the 1994 SPE/IADC Drilling Conference, Dallas, February 15 – 16 (1994)

15. Belavadi, M.N. and Chukwu, G.A.: "Experimental Study of the Parameters Affecting Cuttings Transport in a Vertical Wellbore Annulus," paper SPE 27880 presented at the Western Regional Meeting, Long Beach, March 23 – 25 (1994)

16. Ford, J.T., Gao, E., Oyeneyin, M.B., Peden, J.M., Larrucia, M.B., and Parker, D.: "A

New MTV Computer Package for Hole-Cleaning Design and Analysis," paper SPE 26217 presented at the 1993 SPE Petroleum Computer Conference, New Orleans, July 11-14 (1990)

17. Hemphill, T., and Larsen, T.I.: "Hole-Cleaning Capabilities of Water - and Oil – Based Drilling Fluids: A Comparative Experimental Study," paper SPE 26328 presented at the 1993 SPE Annual Technical Conference and Exhibition, Houston, October 3 – 6 (1993)

18. Azar, J.J, and Alfredo Sanchez, R.: "Important Issues in Cuttings Transport for Drilling Directional Wells," paper SPE 39020 presented at the Fifth Latin American and Caribbean Petroleum Engineering Conference, Rio de Janeiro, August 30 – September 3 (1997)

19. Pilehvari, A.A., Azar, J.J, and Shirazi, S.A.: "State-of- the-Art Cuttings Transport in Horizontal Wellbores," SPE Drill. & Completion 14 (3), pp. 196-200, (September 1999).

20. Li, Y., and Kuru, E.: "Numerical Modeling of Cuttings Transport with Foam in Vertical Wells," paper 2003-066 presented at the Petroleum Society"s Canadian International Petroleum Conference 2003, Calgary, June 10 – 12 (2003)

21. Yu, M., Melcher, D., Takach, N., Miska, S.Z., and Ahmed, R.: "A New Approach to Improve Cuttings Transport in Horizontal and Inclined Wells," paper SPE 90529 presented at the 2004 SPE Annual Technical Conference and Exhibition, Houston, September 26 – 29 (2004)

22. Mirhaj, S.A., Shadizadeh, S.R., and Fazaelizadeh, M.: "Cuttings Removal Simulation for Deviated and Horizontal Wellbores," paper SPE 105442 presented at the 15th SPEMiddle Oil & Gas Show and Conference, Bahrain, March 11 – 14.

23. Bourgoyne, A. T., Chenevert, M. E., Millheim, K. K., and Young, F. S.: " Applied Drilling Engineering". Society of Petroleum Engineers, Richardson, (1986)

24 Chukwu, G. A.: " Drilling and Well Completion", unpublished lecture note. African University of Science and Technology, Abuja. (2010)

25 Ranjbar, R.: " Cuttings Transport in Inclined and Horizontal Wellbore". MSc. Thesis, University of Stavanger, June 2010.

26 Mbama, H. A.: " Gas Entrainment and Hole Cleaning of Low Viscosity, Non-Dispersed Mud Systems". MSc Thesis, University of Alaska, Fairbanks, May 2008.

27 Adari, R. B., Miska, S., Kuru, E., Bern, P., and Saasen, A.: " Selecting Drilling Fluid Properties and Flow Rates for Effective Hole Cleaning in High-Angle and Horizontal Wells", paper SPE 63050 presented at the 2000 SPE Annual Technical Conference and Exhibition held in Dallas, Texas, October 1 – 4 (2000)

28 Kamp, A. M. and Rivero, M.: "Layer Modeling for Cuttings Transport in Highly Inclined Wellbores", paper SPE 53942 presented at the 1999 SPE Annual Technical Conference and Exhibition, Caracas, April 21-23 (1999)

29 Gavignet, A.A. and Sobey, I.J.: "Model Aids Cuttings Transport Prediction," Journal of Petroleum Technology (JPT), pp. 916-921, September (1989)

APPENDIX A

Matlab Codes Used in Generating Values for the Larsen et al. Method

```
Dpipe= input('The Drillpipe Diameter in inches = ');
%Dhole= input('The Hole Diameter in inches = ');
ROP= input('The Rate of Penetration in ft/hr = ');
pm=input('The Mud Weight in ppg = ');
PV= input('The Plastic Viscosity = ');
YP= input('The Yield Point = ');
Dcutt= input('The cuttings size in inches = ');
%Initialize vs1, vs2
vs1=0;
vs2=0;
for ang=55:5:90
    for ann_cl =5:5:50
        annular_clearance=ann_cl/10;
        Dhole= Dpipe+ ann_cl/10;
        Dratio=Dpipe/Dhole;
        vcut=1/((1-(Dratio)^2)*(0.64+(18.18/ROP)));
        %Determination of Slip Velocity
        for i=1:20
            if (vs2-vs1 <=0.01)
                Vcrit=vs1+vcut;
                % Determination of Apparent Viscosity
                Ddiff=Dhole-Dpipe;
                ua=PV+5*YP*Ddiff/Vcrit;
                % calculation of vs2
                if (ua>53)
                    vs2=0.02554*(ua-53)+3.28;
                else
                    vs2=(0.00516*ua)+3.006;
                end
                vs1=vs2;
            end
        end
        %Correction factor for angle
        Cang=(0.0342*ang-0.000233*ang^2-0.213);
        %correction factor for cuttings size
        Csize=-1.04*(Dcutt)+1.286;
        %Correction factor for mud weight
        if  (pm>=8.57);
```

```
            Cmwt=(1-0.0333*(pm-8.7));
        else
            Cmwt=1;
        end
        vslip=(vs2*Cang*Csize*Cmwt);
        vmin=vslip+vcut;
        tratio=1-vslip/vmin;
        qm = 2.448*vmin*(Dhole^2-Dpipe^2);
        ang
        annular_clearance
        vcut;
        vmin
        tratio
        qm
    end
end
```

APPENDIX B

Data Obtained from the Iterative Method of Larsen et al for Plotting Figures 4.1, 4.2 and 4.3

Dpipe=	2.375	inches									
Angle	**Ann cl**	**vcut**	**vmin**	**tratio**	**qm**	**Angle**	**Ann cl**	**vcut**	**vmin**	**tratio**	**qm**
55	0.5	3.224	6.2252	0.5179	40.00314	60	0.5	3.224	6.3406	0.5085	40.7447
	1	2.0283	5.0501	0.4016	71.08521		1	2.0283	5.1663	0.3926	72.72084
	1.5	1.6399	4.6831	0.3502	107.4771		1.5	1.6399	4.8001	0.3416	110.1623
	2	1.4517	4.5163	0.3214	149.2547		2	1.4517	4.6341	0.3133	153.1477
	2.5	1.3425	4.4284	0.3032	196.4881		2.5	1.3425	4.5471	0.2953	201.7548
	3	1.2723	4.3793	0.2905	249.2522		3	1.2723	4.4987	0.2828	256.048
	3.5	1.2239	4.3517	0.2812	307.6043		3.5	1.2239	4.472	0.2737	316.1078
	4	1.1889	4.3374	0.2741	371.6284		4	1.1889	4.4584	0.2667	381.9957
	4.5	1.1626	4.3315	0.2686	441.3712		4.5	1.1626	4.4533	0.2611	453.7824
	5	1.1424	4.3314	0.2637	516.9093		5	1.1424	4.454	0.2565	531.5404
Angle	**Ann cl**	**vcut**	**vmin**	**tratio**	**qm**	**Angle**	**Ann cl**	**vcut**	**vmin**	**tratio**	**qm**
65	0.5	3.224	6.4197	0.5022	41.25299	70	0.5	3.224	6.4624	0.4989	41.52738
	1	2.0283	5.2459	0.3866	73.84129		1	2.0283	5.2889	0.3835	74.44656
	1.5	1.6399	4.8803	0.336	112.0029		1.5	1.6399	4.9236	0.3331	112.9966
	2	1.4517	4.7149	0.3079	155.818		2	1.4517	4.7585	0.3051	157.2589
	2.5	1.3425	4.6284	0.2901	205.3621		2.5	1.3425	4.6723	0.2873	207.31
	3	1.2723	4.5806	0.2778	260.7094		3	1.2723	4.6248	0.2751	263.2251
	3.5	1.2239	4.5544	0.2687	321.9323		3.5	1.2239	4.5989	0.2661	325.0778
	4	1.1889	4.5413	0.2618	389.0986		4	1.1889	4.5862	0.2592	392.9456
	4.5	1.1626	4.5368	0.2563	462.2908		4.5	1.1626	4.5819	0.2537	466.8864
	5	1.1424	4.538	0.2517	541.5649		5	1.1424	4.5834	0.2492	546.983
Angle	**Ann cl**	**vcut**	**vmin**	**tratio**	**qm**	**Angle**	**Ann cl**	**vcut**	**vmin**	**tratio**	**qm**
75	0.5	3.224	6.4689	0.4984	41.56915	80	0.5	3.224	6.4391	0.5007	41.37766
	1	2.0283	5.2954	0.383	74.53805		1	2.0283	5.2654	0.3852	74.11577
	1.5	1.6399	4.9302	0.3326	113.1481		1.5	1.6399	4.9	0.3347	112.455
	2	1.4517	4.7651	0.3046	157.477		2	1.4517	4.7347	0.3066	156.4724
	2.5	1.3425	4.679	0.2869	207.6072		2.5	1.3425	4.6483	0.2888	206.2451
	3	1.2723	4.6315	0.2747	263.6065		3	1.2723	4.6006	0.2765	261.8477
	3.5	1.2239	4.6057	0.2657	325.5585		3.5	1.2239	4.5746	0.2675	323.3602
	4	1.1889	4.593	0.2589	393.5282		4	1.1889	4.5617	0.2606	390.8465
	4.5	1.1626	4.5888	0.2534	467.5895		4.5	1.1626	4.5573	0.2551	464.3798
	5	1.1424	4.5903	0.2489	547.8064		5	1.1424	4.5586	0.2506	544.0233
Angle	**Ann cl**	**vcut**	**vmin**	**tratio**	**qm**	**Angle**	**Ann cl**	**vcut**	**vmin**	**tratio**	**qm**

85	0.5	3.224	6.3729	0.5059	40.95226	90	0.5	3.224	6.2705	0.5142	40.29423
	1	2.0283	5.1988	0.3901	73.17831		1	2.0283	5.0957	0.398	71.72707
	1.5	1.6399	4.8329	0.3393	110.9151		1.5	1.6399	4.729	0.3468	108.5306
	2	1.4517	4.6671	0.311	154.2383		2	1.4517	4.5625	0.3182	150.7815
	2.5	1.3425	4.5803	0.2931	203.2279		2.5	1.3425	4.475	0.3	198.5558
	3	1.2723	4.5322	0.2807	257.9547		3	1.2723	4.4261	0.2875	251.9159
	3.5	1.2239	4.5057	0.2716	318.4899		3.5	1.2239	4.3989	0.2782	310.9406
	4	1.1889	4.4923	0.2647	384.9003		4	1.1889	4.3848	0.2711	375.6897
	4.5	1.1626	4.4874	0.2591	457.2571		4.5	1.1626	4.3793	0.2655	446.2419
	5	1.1424	4.4883	0.2545	535.6337		5	1.1424	4.3795	0.2608	522.6495

APPENDIX C

Data Obtained from Using the New Model (Equation 3.25) to Develop Figure 4.4

Dpipe= **2.375**
ROP (ft/h)= **54**

flowrate_1 (gal/min)= **100**
flowrate_2 (gal/min)= **300**
flowrate_3 (gal/min)= **500**
flowrate_4 (gal/min)= **700**
flowrate_5 (gal/min)= **900**

Ann Clr	**Va_1**	**Va_2**	**Va_3**	**Va_4**	**Va_5**
0.5	15.7935766	47.3807298	78.967883	110.5550362	142.1421894
0.75	10.05045784	30.15137351	50.25228918	70.35320485	90.45412052
1	7.210111056	21.63033317	36.05055528	50.47077739	64.89099951
1.25	5.52775181	16.58325543	27.63875905	38.69426267	49.74976629
1.5	4.422201448	13.26660434	22.11100724	30.95541013	39.79981303
1.75	3.644671523	10.93401457	18.22335761	25.51270066	32.80204371
2	3.070973228	9.212919683	15.35486614	21.49681259	27.63875905
2.25	2.632262767	7.8967883	13.16131383	18.42583937	23.6903649
2.5	2.287345576	6.862036729	11.43672788	16.01141904	20.58611019
2.75	2.010091567	6.030274702	10.05045784	14.07064097	18.0908241
3	1.783145745	5.349437235	8.915728725	12.48202022	16.04831171
3.25	1.594543791	4.783631374	7.972718956	11.16180654	14.35089412
3.5	1.435779691	4.307339073	7.178898454	10.05045784	12.92201722
3.75	1.300647485	3.901942454	6.503237423	9.104532392	11.70582736
4	1.184518245	3.553554735	5.922591225	8.291627715	10.6606642
4.25	1.083872904	3.251618712	5.419364519	7.587110327	9.754856135
4.5	0.995991317	2.987973951	4.979956585	6.971939219	8.963921854
4.75	0.918739913	2.756219739	4.593699565	6.431179391	8.268659217
5	0.850423355	2.551270066	4.252116777	5.952963487	7.653810198

APPENDIX D

Data Obtained from Using the New Model (Equation 3.28) to Develop Figure 4.5

mud density = 8.75
Avr cutting density = 20

ROP (ft/hr)	mean mud density
0	8.80725
10	8.8272525
20	8.847255
30	8.8672575
40	8.88726
50	8.9072625
60	8.927265
70	8.9472675
80	8.96727
90	8.9872725
100	9.007275
110	9.0272775
120	9.04728
130	9.0672825
140	9.087285
150	9.1072875
160	9.12729
170	9.1472925
180	9.167295
190	9.1872975
200	9.2073
210	9.2273025
220	9.247305
230	9.2673075
240	9.28731
250	9.3073125
260	9.327315
270	9.3473175
280	9.36732
290	9.3873225
300	9.407325

310	9.4273275
320	9.44733
330	9.4673325
340	9.487335
350	9.5073375
360	9.52734
370	9.5473425
380	9.567345
390	9.5873475
400	9.60735

APPENDIX E

Data Obtained from Using the New Model (Equation 3.25) to Develop Figure 4.6

			flowrate_1 (gal/min)=	**100**	
Dpipe=	**5**		flowrate_2 (gal/min)=	**300**	
ROP (ft/h)=	**33**		flowrate_3 (gal/min)=	**500**	
			flowrate_4 (gal/min)=	**700**	
			flowrate_5 (gal/min)=	**900**	
Ann Clr (inches)	**Va_1 (ft/s)**	**Va_2 (ft/s)**	**Va_3(ft/s)**	**Va_4(ft/s)**	**Va_5 (ft/s)**
0.5	7.866979	23.60093798	39.3348966	55.06885528	70.80281
0.75	5.122684	15.36805264	25.6134211	35.85878948	46.10416
1	3.754695	11.26408403	18.7734734	26.28286275	33.79225
1.25	2.937006	8.811016844	14.6850281	20.5590393	26.43305
1.5	2.394298	7.182894167	11.9714903	16.76008639	21.54868
1.75	2.00859	6.025771398	10.0429523	14.06013326	18.07731
2	1.720902	5.162705182	8.60450864	12.04631209	15.48812
2.25	1.498472	4.495416757	7.49236126	10.48930577	13.48625
2.5	1.321653	3.96495758	6.60826263	9.251567687	11.89487
2.75	1.177943	3.533830285	5.88971714	8.245603999	10.60149
3	1.059016	3.177049343	5.29508224	7.413115134	9.531148
3.25	0.959109	2.877327707	4.79554618	6.713764649	8.631983
3.5	0.874109	2.622326442	4.37054407	6.118761698	7.866979
3.75	0.801002	2.403004594	4.00500766	5.607010719	7.209014
4	0.737529	2.212587935	3.68764656	5.162705182	6.637764
4.25	0.681967	2.045901744	3.40983624	4.773770736	6.137705
4.5	0.632975	1.898926044	3.16487674	4.430827436	5.696778
4.75	0.589497	1.768491338	2.94748556	4.126479789	5.305474
5	0.550689	1.652065658	2.75344276	3.854819869	4.956197