Assessment of Drilling Fluid Hole Cleaning Capacity in Horizontal Directional Drilling – A Parametric Study of the Effects of Drilling Fluid Additives

by

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Abstract

Horizontal directional drilling (HDD) as one of the most popular trenchless technology has seen a rapid growth during the past decades. Hole cleaning has been one of the most challenging problems of the directional well drilling in the oil and gas industry. As an outgrowth of the directional drilling technique from the petroleum industry, HDD faces the similar challenges. Transporting drilled solids (i.e. cuttings) out of the borehole is more difficult in HDD due to its unique features such as large borehole diameter and associated low fluid velocity (i.e. laminar flow regime). Insufficient hole cleaning will lead to various costly operational problems such as high torque and drag, slow drilling rate and stuck pipe as well as environmental issues.

To improve the understanding of cuttings transport in HDD annulus, a comprehensive review of the hole cleaning related researches in directional drilling of oil and gas wells (including limited studies in HDD industry,) has been conducted. The review focused on the factors affecting hole cleaning performance with relatively high effectiveness and controllability to provide guidelines for future research and field applications. Annular flow velocity, drilling fluid rheological properties and drill pipe rotation were found to be the most influential factors. The annular velocity profile, which is dependent on the annular flow velocity as well as the rheological properties of drilling fluid plays an important role in cuttings transport in laminar flow regime.

Effect of drilling fluid rheological properties on its hole cleaning capacity was chosen as the major focus of interest in this study. A new evaluation method of drilling fluid hole cleaning capacity for Herschel-Bulkley (yield-power-law) type fluids is proposed for HDD applications and compared with conventional hole cleaning indicators. Hole cleaning capacity of the drilling fluid was divided into two components: suspension capacity and sweeping capacity. The high value of yield stress (τ_y) and the width of plug flow velocity profile (plug width, *h*) were used to indicate better suspension capacity while low frictional pressure loss (ΔP) caused by the viscosity of the drilling fluid was used to indicate better sweeping capacity. Effect of different additives (bentonite and biopolymer) on the rheological properties of water-based drilling fluids and the hydraulic behaviors, as well as the hole cleaning capacity indicators, were investigated. The commonly used rotational viscometer was used to test the rheological properties of the drilling fluids. And Herschel-Bulkley model was applied to calculate the rheological parameters as well as the hydraulic parameters following the API standards. The experimental results showed that adding more bentonite or biopolymer will both increase the τ_y and ΔP which indicates higher suspension and lower sweeping capacity. Selection of the right concentration should depend on the real conditions like the velocity level, pump capacity, and allowable annular pressure. Samples with higher bentonite concentration and lower biopolymer concentration usually showed better hole cleaning capacity (higher τ_y and lower ΔP). Since lower ΔP not only can enhance the sweeping capacity and widen the plug width but also reduces the risk of hydrofracture and allows higher flow velocity. Considering the huge price difference between the bentonite and biopolymer, the bentonite used in this study is more economical effective in improving hole cleaning capacity of the drilling fluid.

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Chapter 1: Introduction

1.1. Background

Horizontal directional drilling (HDD) is a trenchless technology which can be used to install utilities and pipelines under rivers, constructions and existing underground facilities with minimal surface excavation and disruption (Ariaratnam and Allouche 2000; Yan et al. 2018). Compared to the traditional open-cut method, using HDD technology can significantly reduce the cost and environmental impact in some special areas such as congested urban area, locations near important constructions or when crossing river and mountains (Kennedy et al. 2004). This construction technology has seen rapid development when first transferred from the petroleum industry in the 1970s. Numerous researches have been carried out to enable the HDD construction process being completed safely and efficiently. Based on a recent review (Yan et al. 2018), the three main engineering concerns are pullback load estimation, borehole stability evaluation, and mud pressure prediction. Incorrect estimation of these operational parameters can result in both engineering and environmental problems. However, hole cleaning in HDD process which can also result in the similar serious problems is rarely investigated.

As the drill bit penetrates into the ground, large volume of cuttings will be produced and need to be transported out of the borehole. Insufficient hole cleaning will lead to accumulation of cuttings, blockage of the annular space, increase in drilling torque and drag forces acting on the drill pipe or product pipeline, high annular pressure as well as high risk of hydrofracture and is one of the major causes leading to the stuck pipe (Pilehvari et al. 1999).

Although the cuttings transport has been studied in the petroleum industry for more than half a century in both vertical and horizontal wells, the problems still exist in many drilling operations. The unique features of HDD (i.e. large borehole size and associated low flow velocity, limited pump capacity) make the effective cuttings transport even more difficult in this case. The flow velocity is always identified as the most effective factor in hole cleaning performance (Azar and Sanchez 1997; Busahmin et al. 2017; Iyoho 1980; Pilehvari et al. 1999), however, the large diameter, the restricted pump capacity, and the limited annular pressure are all undesired in improving the flow velocity. Under the low flow velocity condition, conclusions or rules of thumb from the petroleum industry are not fully applicable in solving hole cleaning problems in HDD. Factors affecting hole cleaning performance in previous researches as well as their controllability in HDD practice should be re-evaluated.

The drilling fluid as the only circulated medium in the annulus plays multiple roles in the drilling process, one of which is to carry the cuttings out to the ground surface. Understanding how the drilling fluid properties can influence the cuttings transport in the annulus is helpful to select the proper drilling fluid formulations and to evaluate the effect of different additives on drilling fluid hole cleaning capacity.

1.2. Research Objectives

The main purpose of this study is to better understand the cuttings transport process in HDD annulus to help improve the hole cleaning performance. To achieve this goal, the factors affecting cuttings transport in HDD need to be identified, their effectiveness, controllability as well as interaction among these factors need to be understood. As the drilling fluids are the only carrier medium of the cuttings in the HDD annulus, characterization of the rheological properties of the drilling fluids, how they change with the use of various additives and understanding how the change of rheological properties of the drilling fluids would affect the hole cleaning performance of drilling fluids are the main objectives of this study. Since the interaction between cuttings and the drilling fluid are directly related to fluid's hydraulic behavior in the annulus, which is mainly dependent on its rheological properties and flow velocity, the effect of drilling fluid rheological parameters on its hole cleaning capacity related hydraulic behavior is required to be understood. Based on this, a new evaluation method of drilling fluid hole cleaning capacity can be established for possible use in the optimized selection of drilling fluid additives and the improvement of cuttings transport.

1.3. Methodology

To achieve the objectives of this study, a comprehensive review of cuttings flow patterns and models as well as factors affecting drilling fluid hole cleaning capacity in horizontal wells has been conducted. After identifying the most influential parameters, rheological experiments have been conducted to determine the influence of different components or additives on the rheological properties of the waster-based drilling fluids, which are correlated with their hole cleaning capacity. In this study, the effect of rheological properties together with the hydraulic parameters on cuttings transport are all investigated, and the hole cleaning capacity of the drilling fluid is divided into suspension capacity and sweeping capacity. The results were also compared with conventional hole cleaning performance indices.

The experimental research has two major stages: in the first stage, only various concentrations of bentonite were used as the additive. By controlling the concentration of bentonite, rheological parameters as well as hydraulic parameters have been changed. The effect of bentonite concentration on these parameters were investigated and compared with conventional indicators to provide a deeper insight into the relationship between the drilling fluid properties and its hole cleaning capacity.

For stage two, both bentonite and biopolymer were used to obtain drilling fluids with more variety of properties. The main purpose of this test was to investigate how the biopolymer will modify the rheological properties of drilling fluid as well as its hydraulic behavior and hole cleaning capacity. The Herschel-Bulkley yield stress together, the frictional pressure loss and the width of the plug velocity profile (also called plug width) are employed to provide a more specific evaluation approach of drilling fluid hole cleaning capacity.

1.4. Outline of Thesis

This thesis has the following structure:

Chapter 1: Introduction: A brief background of the research topic, the objectives and methodology as well as the structure of the thesis were introduced.

Chapter 2: Literature review: A review of the hole cleaning researches in HDD industry as well as relevant researches on highly inclined and horizontal wells in petroleum industry was provided. Cuttings transport patterns and the basic models were introduced. The most influential factors were discussed. Based on the features of HDD, suggestions for future researches on hole cleaning were proposed.

Chapter 3: Rheological properties of clay-base drilling fluids and evaluation of their hole cleaning performances in horizontal directional drilling were discussed. Drilling fluids with different bentonite concentration were tested by using API rotational viscometer. Rheological models recommended by API were used to obtain the rheological parameters and the goodness of fit for each method was compared. Hole cleaning capacity of drilling fluid was divided into two components: suspension capacity indicated by yield stress and plug width and sweeping capacity which is related to the fluid viscometer and is represented by frictional pressure loss (ΔP). Effect of bentonite concentration on the drilling fluid rheological parameters and hydraulic behavior as well as their effect on hole cleaning capacity was discussed from multiple aspects.

Chapter 4: Effects of biopolymer additive on hole cleaning capacity of water-based drilling fluids in horizontal directional drilling: a commonly used biopolymer additive, Xanthan Gum, was added to water-based drilling fluid with different bentonite concentration. Effect of bentonite and biopolymer on the rheological properties as well as the hydraulic parameters mentioned in the chapter 3 were investigated and discussed. A systematic evaluation method was presented by considering yield stress (τ_y), plug width (h) and frictional pressure loss (ΔP) together. Bentonite was found to be more economical effective in improving the hole cleaning capacity the more expensive biopolymer.

Chapter 5: Conclusions and future research: The most important results of the study were summarized and the highlighted conclusions were presented. Suggestions for future hole cleaning research in HDD were made.

Chapter 2: Literature Review

2.1. Introduction

Horizontal directional drilling (HDD) is one of the trenchless construction methods that can be used to install underground pipelines and utilities with minimal surface excavation (Ariaratnam et al. 2007). Due to its advantages on minimizing the traffic interruption as well as reducing damage to the existing infrastructures, HDD has seen a rapid development since the first HDD installation in 1971 (Cheng and Polak 2007; David 2005; Yan et al. 2018). One of the most important keys to conducting a successful HDD construction is efficiently transporting the cuttings out of the borehole, as known as hole cleaning. Inadequate hole cleaning will cause a series of problems like reducing borehole diameter, rising annular pressure, increasing torque and drag force as well as leading to stuck pipe. Osbak (2012) conducted an investigation on the risks associated with HDD among 100 projects and the results showed that "Tripping to Clean/Gauge Hole" has the highest frequency of occurrence and "Product Line Stuck" has the most significant impact on the project schedule, both of which are related to poor hole cleaning.

HDD technology is an outgrowth of the petroleum industry in which the hole cleaning topic has been widely investigated (David 2005). This can be taken advantage of by HDD industry. However, the features of HDD make the hole cleaning process even hard. First, HDD wells have a high angle of inclination from the vertical, 70 to 90 degrees, which dramatically increases the requirement of annular fluid flow rate to lift the cuttings (Peden et al. 1990). Besides, the diameter of the borehole in HDD can reach over 1.5 m (60 in) in some large-diameter HDD crossing, which needs an even larger annular space and further lower the flow rate (Shu et al. 2015). Moreover, the buried depth of HDD pipelines is usually less than 60 m (Baik et al. 2003) which is much shallower compared with oil and gas wells. Generally, the borehole becomes less stable with decreasing depth. Therefore, any hole cleaning improvement measures that will simultaneously increase the annular pressure, such as increasing pump rate or using high-density drilling fluid, will be restricted (Bayer 2005).

The chapter provides reviews of the hole cleaning researches in the HDD industry as well as relevant researches on high inclined and horizontal wells in the petroleum industry. Cuttings transport patterns and the basic models are introduced. The influential factors are presented, and the most effective and controllable factors are discussed. Based on the features of HDD, suggestions for future researches on hole cleaning are proposed.

2.2. Cuttings Transport Procedure

Since the early 1980's, the cuttings transport in inclined and horizontal wells started to catch more attentions and lots of experiments as well as models on cuttings transport were developed (Clark and Bickham 1994). The mechanism of cuttings bed erosion, the cuttings transport patterns observed from experiments as well as the layer-models developed to predict cuttings and fluid behaviors are introduced.

2.2.1. Mechanism of Cuttings Bed Erosion

The mechanism of cuttings bed erosion is usually explained by a well-known mechanistic model which consists of two types of forces acting on a single particle on the cuttings bed surface: mobilizing forces and resistive forces (Bizhani and Kuru 2018a) (Figure 2.1).

The mobilizing forces cause the cuttings to be moved from the cuttings bed which mainly include the buoyancy force (F_b) and hydrodynamic force (lift, F_L and drag, F_d) due to the flow of the fluid. The resistive forces hold the particle in place which includes gravity force (F_g), plastic force (F_p) for viscoelastic fluid and Van der Waals force (F_{van}) in case of small particles (Clark and Bickham 1994; Duan et al. 2009; Ramadan et al. 2003). When the mobilizing forces exceed the resistive forces, the particle will be rolled or lifted from its resting place, which can be regarded as the initiation of the cuttings bed erosion(Clark and Bickham 1994). The hydrodynamic forces depend on the flow conditions and drilling fluid properties, generally, these forces will increase with higher flow velocity and drilling fluid viscosity. In terms of the resistive forces, for a given condition (cuttings characteristics are constant), the gravity force and the Van der Waals forces are not variable. The plastic force is due to the elastic property of the stagnant fluid in the particle pores, which depends on the yield stress of fluid (Ramadan et al. 2003). Saasen and Løklingholm (2002) and Saasen (1998) reported that polymers in drilling fluid usually react in the bed and form a crosslinked structure with the bed material to make the bed erosion more difficult. It was also reported that viscoelastic fluids will exert an additional compressive force acting in the direction perpendicular to the flow direction which will further enhance the resistive force on the particle (Bird et al. 1987). Bizhani and Kuru (2018a) believed that this compressive force is the main reason causing the delay of the onset of the bed erosion with the increasing polymer concentration of the fluid.

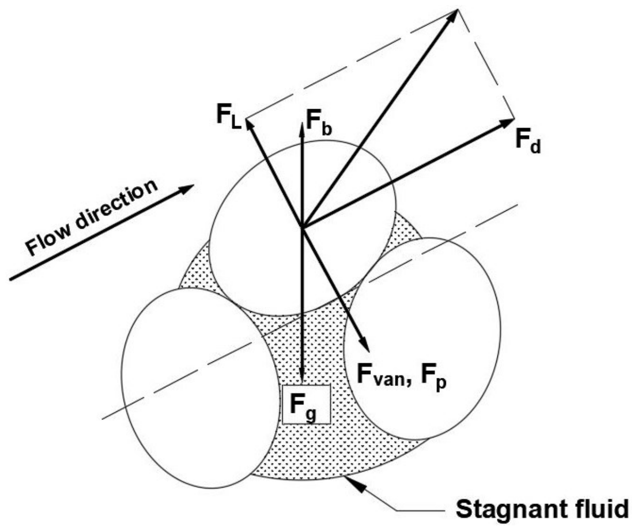
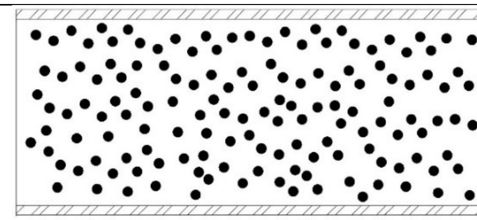
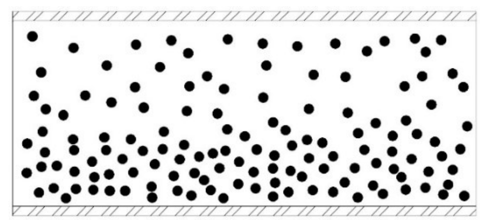
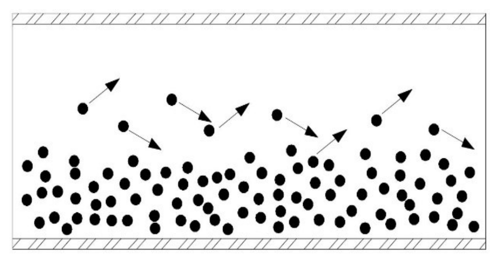
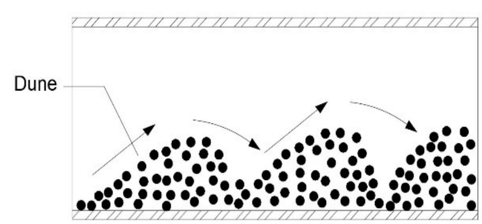


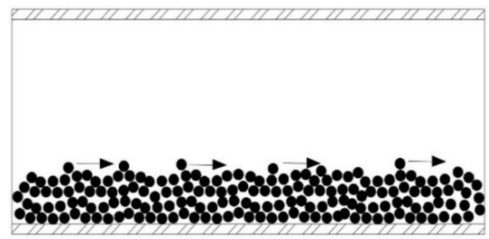
Figure 2.1 Schematics of forces acting on a single particle in the cuttings bed

2.2.2. Cuttings Transport Patterns

Cuttings transport in the annulus can be identified as solid-liquid mixture transport (Peden et al. 1990). A good hole cleaning performance is to prevent cuttings from falling out from the mixture to form either stationary or downward sliding cuttings beds. Based on previous experimental observations in inclined and horizontal flow loops (Ford et al. 1990; Khatibi et al. 2018; Leising and Walton 2002; Luo and Yuejin 1988), the flow patterns of this mixture can be generally classified into four categories: homogeneous/heterogeneous suspension, saltation, moving bed and stationary bed, in which cuttings are assumed to be non-cohesive. The brief descriptions as well as the

Table 2.1. Cuttings transport patterns

Transport patterns	Description	Schematics
Homogeneous/Heterogeneous Suspension	When flow velocity is high enough, the fluid can fully suspend the cuttings. Due to density difference of cuttings, the heterogeneous flow pattern is more likely to occur in horizontal wells.	 Homogeneous flow  Heterogeneous flow
Saltation	When cuttings cannot be fully suspended, the cuttings will be lifted and then fall back to the lower cuttings bed which seems like jumping along the bed surface, known as “saltation”. The occurrence of saltation is also regarded as the sign of initiation of bed erosion.	
Moving Bed	When the settlement force gradually dominants, the cuttings tend to travel together in forms of separated moving beds (dunes) or continuous moving bed	

Transport patterns	Description	Schematics
	(e.g the dunes will be connected when velocity further increases).	
Stationary Bed	If the lifting force further decreases, a stationary bed will form on the low-side of the annulus. The cuttings on the surface of the bed will roll and slide forward while the cuttings inside the bed remain stationary. A continuously built-up of the bed will finally block the annulus and get the drill rods or the product pipes stuck.	

It is worth noting that these flow patterns are based on the assumption that cuttings are transported in the annulus without pipe rotation and the erosion of the cuttings bed is caused by the dynamic effect of drilling fluid. However, pipe rotation is usually indispensable in HDD annulus. According to the observation of the laboratory tests conducted by Khatibi et al. (2018), when pipe rotation was considered, the radial drag force generated by pipe rotation helped to lift cuttings from the bed into suspension, thus the velocity for initiating each pattern would be reduced, and stationary bed, as well as separated moving bed, would disappear. In this case, the requirement of drilling fluid for eroding cuttings bed will be diminished for a certain extent, which means how to keep the cuttings in suspension after them being lifted becomes more important in the HDD application

2.2.3. Cuttings Transport Models

In order to predict cuttings bed height, pressure drops and cuttings concentration profile, researchers in oil and gas industry developed lots of versions of layer-model (Brown et al. 1989; Doron and Barnea 1993; Gavignet and Sobey 1989; Martins et al. 1996; Nguyen and Rahman 1996; Wilson 1970). These models are based on mass balance and momentum balance equations as well as the related closure equations (Bizhani and Kuru 2018b; Kelessidis and Mpandelis 2003; Li and Luft 2014). Generally, they can be divided into two categories: two-layer models, three-layer models.

Based on the research of Wilson (1970) on slurry transport in pipes, Gavignet and Sobey (1989) introduced a two-layer model for the cuttings transport in the annulus. They assumed a cuttings bed at the bottom with pure mud above it in an eccentric annulus. Later, this model was modified by different researchers: Martins and Santana (1992) presented a two-layer model that allows the cuttings to be suspended in the upper layer and Martins et al. (1996) extended the model to non-Newtonian fluids by adapting yield-power law. Santana et al. (1998) used experiments to determine the interfacial friction factor between the cutting bed and the suspension, which showed significant influence in cuttings bed height prediction. They also emphasized the importance of drilling fluid rheology by using five different rheological models in the prediction.

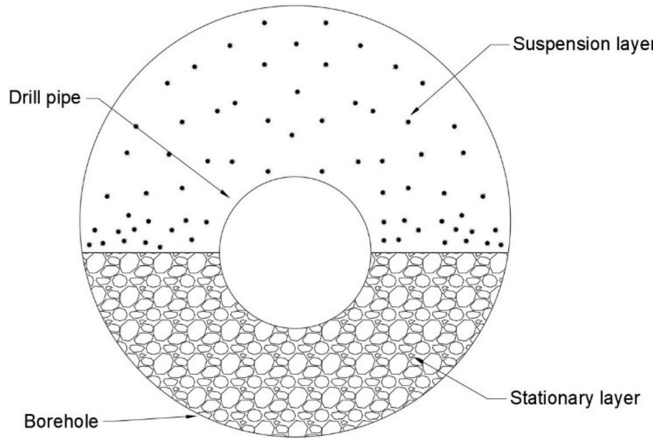


Figure 2.2. Two-layer model for cuttings transport in the annulus

For slurry flow in pipes, due to the inability of the two-layer model to accurately predict the existence of a stationary bed at low flow rates, Doron and Barnea (1993) extended their two-layer model to a three-layer model with a stationary bed (uniform concentration of cuttings) at the bottom, a moving bed at the middle, and a heterogeneous mixture layer at the top. Doron's work led to the development of the three-layer model in the annulus (Kelessidis and Mpandelis 2003). Nguyen and Rahman (1996) introduced a three-layer model. This model consists of a stationary bed (uniform concentration of cuttings) at the bottom of the annulus, a dispersed layer (the cuttings concentration is varied) above it, and a clear mud layer at the top. However, this state is not constant. As flow velocity increases gradually, the clear mud layer will become a heterogeneous-suspension layer, the stationary layer may disappear and the model will be simplified into a two-layer model. Finally, when extremely high velocity is reached all the cuttings will be suspended to form a "single-layer" pattern. Hyun et al. (2000) introduced a three-segment model and applied the one-layer model for vertical wells, a two-layer model for medium inclination wells and three-layer model for horizontal wells.

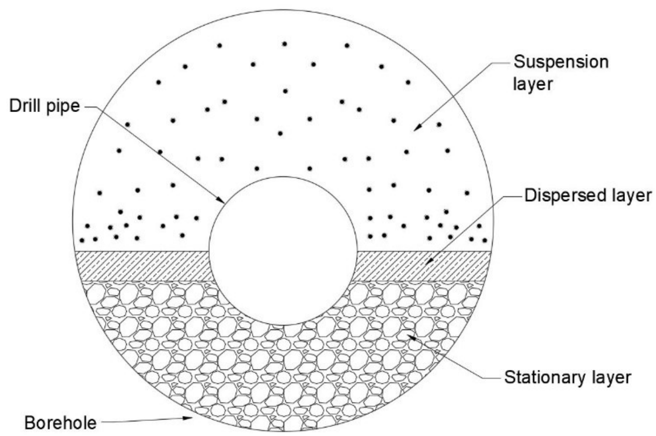


Figure 2.3. Three-layer model for cuttings transport in the annulus

Based on the three-layer model developed by Nguyen and Rahman (1996), Shu et al. (2015) introduced a model for large-diameter HDD boreholes. It was concluded that due to the relatively low flow rate in HDD boreholes, the dispersed layer will not exist, which means the erosion of the cuttings bed due to fluid flow was neglected. Instead of dividing the borehole by layers, they build the model based on the transport mechanism of different size of cuttings. The finest cuttings (<0.1mm) which will be suspended and transported out of the borehole; the medium-sized cuttings (between 0.1 and 2.0 mm) which cannot be fully suspended but is able to be transported out of the hole before settling to the bottom by adjusting drilling parameters; and the oversize cuttings (>2.0 mm) which will settle quickly but may be stirred up during the subsequent reaming operation and transported by saltation or be reground into smaller particles. This model simplified the three-layer model by only considering the suspension pattern which needs to be verified by more laboratory tests. Besides, the rotation of the drill pipe was not taken into account, which may have a positive improvement in cuttings transport (Sanchez et al. 1997). For more detail information about the layer models, one can refer to the reviews from Kelessidis and Mpandelis (2003) and Li and Luft (2014).

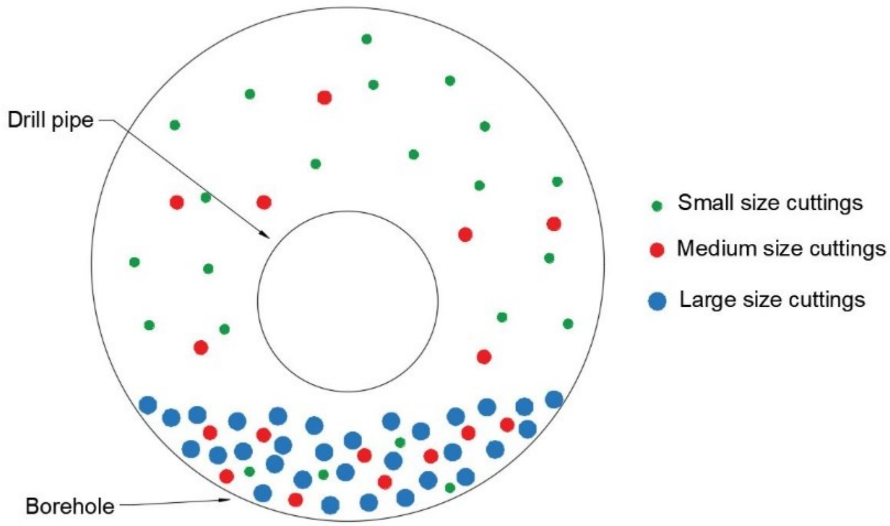


Figure 2.4. Annular cuttings transport model for large-diameter HDD borehole (Shu et al. 2015)

2.3. Main Influential Factors for Hole Cleaning and Their Field Controllability

Compared to vertical well, hole cleaning researches in high inclined and directional wells are more relevant to HDD. During the past decades, researchers have done plenty of experiments to investigate the parameters that impact the hole cleaning performance in directional oil and gas wells. The main influential factors can be classified into six categories: (1) Flow velocity; (2) Drilling fluid properties (density and rheological properties); (3) Hole inclination and annular dimensions; (4) Drill pipe rotation and eccentricity; (5) Rate of penetration (ROP); (6) Cuttings characteristics (size, shape and density) (Azar and Sanchez 1997; Busahmin et al. 2017; Pilehvari et al. 1999).

The above key variables possess different degrees of influence and controllability in HDD operation. In conventional oil and gas well drilling, Luo and Yuejin (1988) divided the main controlling factors into two general groups: controllable (flow velocity and flow regime, drilling fluid properties, hole inclination, drill pipe rotation and ROP) and uncontrollable (cuttings characteristics, annular dimensions). Adari et al. (2000) gave a more visualized graph based on the degree of influence and controllability in the field for each factor. Although these conclusions from the petroleum industry are not fully applicable to HDD, they are still a good reference. Due to the limited laboratory and field experiments in the HDD industry, it is difficult to quantify the influence and controllability of each factor. Therefore, based on the feature of HDD and the literature from the petroleum industry (Adari et al. 2000; Luo and Yuejin 1988), the author divided the influential factors into two general groups. Group one consists of the most controllable factors like flow velocity, drilling fluid rheological properties and drill pipe rotation. Group two contains the uncontrollable and less controllable factors including hole inclination and annular dimensions, drill pipe eccentricity, cuttings characteristics, ROP and drilling fluid density.

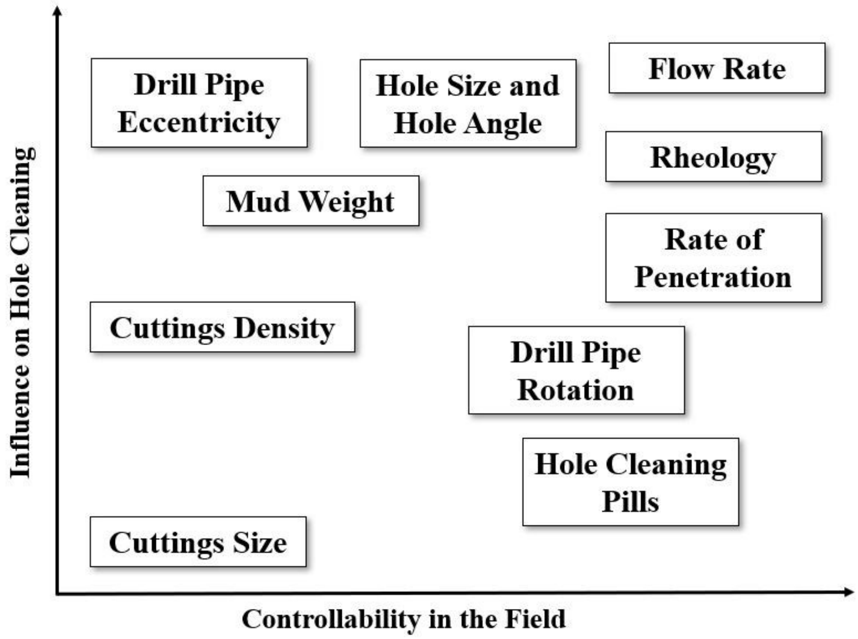


Figure 2.5 Key variables controlling cuttings transport (Adari et al. 2000)

If the hole cleaning problem is caused by the uncontrollable factors, in order to optimize the hole cleaning performance, the controllable ones need to be well understood and adjusted (Luo and Yuejin 1988). The uncontrollable and less controllable factors will be briefly introduced while more detailed discussion about the factors with high controllability will be presented in the following sections.

2.4. Uncontrollable and Less Controllable Factors

2.4.1. Hole Inclination and Annular Dimensions

In a series of flow loop experiments conducted by Tomren et al. (1986), annular cuttings concentration vs. borehole inclination were investigated under different flow rate. The results showed that cuttings concentration generally increase as the inclination varied from vertical to horizontal except for the low flow rate situation where the critical inclination appeared to be within the range from 40° to 60°. This phenomenon was also observed by other researchers (Li and Walker 2001; Peden et al. 1990). This is because in this angle range the cuttings bed tends to slide down under the force of gravity (Li and Walker 2001; Tomren et al. 1986). Although in HDD wellbores the inclination depends on the bore path design (entry and exit angle), which ranges from 70 to 90 degrees from the vertical when compared to vertical wells, the cuttings transport in HDD wells are much harder than it is in horizontal wells. The minimum flow velocity, also called critical flow rate (CFR) or minimum transport velocity (MTV), to keep the hole clean was found to be much higher in horizontal wells (Ford et al. 1990; Leising and Walton 2002; Luo and Yuejin 1988). Moreover, the diameter of the borehole in HDD is usually larger than that in oil and gas wells, which can reach over 1.5 m (60 in), and this factor will further lower the available flow velocity in the annulus (Shu and Ma 2015). The diameter and length of the borehole are also uncontrollable since they are all highly dependent on the dimension of the product pipe.

2.4.2. Drill Pipe Eccentricity

Eccentricity describes how much the drill pipe is off center in the borehole, which is another uncontrollable factor. Positive eccentricity refers to the situation where the drill pipe is closer to the bottom of the borehole, and vice versa. The eccentricity results in different flow areas in the annulus, take the positive eccentricity as an example, more fluid will be pushed to the supper side which is more spacious while the flow in the lower side will be hindered (Luo and Yuejin 1988). In vertical wells, the eccentricity of the drill pipe shows the minor effect on cuttings transport since the increased flow rate in the enlarged side will compensate the flow reduction in the narrower side (Thomas et al. 1982; Tomren et al. 1986). However, in horizontal wells, the drill pipe tends to lie at the bottom of the annulus due to the gravity force. Low flow rate in the narrow gap near the bottom will slow down the transport of the cuttings which will be deposited rapidly (Walker and Li 2000). We cannot always keep the drill pipe concentric during the drilling process, fortunately, the drill pipe will be bent and rotated in HDD annulus which can cause frequent fluctuations in drill pipe eccentricity and can significantly improve the flow distribution to diminish the negative impact caused by high eccentricity. The effect of drill pipe rotation will be discussed in detail later.

2.4.3. Cuttings Characteristics

The cuttings characteristics affecting the hole cleaning include their size, density and shape. There are very limited researches about the effect of cuttings density and shapes on hole cleaning performance while most of the researchers focused on the impact of cuttings size.

For higher cuttings density, it is more difficult to either suspend the cuttings or to lift it from the cuttings bed due to the enhanced gravity effect (Ozbayoglu et al. 2009). As for the shape of the cuttings, a parameter "sphericity" (ψ) was usually used to describe effect of the cuttings shape (Luo and Yuejin 1988). The less spherical the cutting, the smaller the ψ and the maximum value of ψ is 1 when the cutting is a sphere. Al-Kayiem et al. (2010) found cuttings with higher ψ are easier to be cleaned out.

As for the effect of cuttings size, there have been some conflicting results. Some field and laboratory experiments indicate that smaller cuttings need more effort to be transported (Larsen 1990; Parker 1987) while the others found smaller cuttings are easier to be mobilized (Al-Kayiem et al. 2010; Ford et al. 1990; Peden et al. 1990). Walker and Li

(2000) and Wilson and Judge (1978) found there was a critical particle diameter while using water as the transport medium. When the particle diameter is above this critical value smaller size is harder to clean and vice versa. Walker and Li (2000) gave a critical value of 0.76 mm while Wilson and Judge (1978) gave a value of 0.5mm. However, when polymer fluids were used by Walker and Li (2000), smaller cuttings were always found easier to be transported. Similar results were also reported by Duan et al. (2008) that better hole cleaning was achieved with smaller cuttings when PAC solutions were used. Bassal (1995) and Walker and Li (2000) both pointed it out that the effect of the cuttings sized is highly dependent on other parameters like flow rate, drilling fluid properties and borehole geometry,

2.4.4. The Rate of Penetration (ROP)

The ROP is directly related to cuttings production per unit time in the annulus. Higher ROP produces more cuttings which need a higher flow rate and more time to be cleaned out (Luo and Yuejin 1988; Nazari et al. 2010; Sifferman and Becker 1992). Although reducing ROP may benefit the hole cleaning performance, it will also extend the drilling time which increases the cost. Therefore, ROP should be kept in a reasonable range to reduce the cuttings concentration while not impairing cost efficiency.

2.4.5. Drilling Fluid Density

The main function of drilling fluid density is to balance the ground pressure and to provide stability to the borehole, which is highly dependent on the buried depth and ground properties (Azar and Sanchez 1997; Luo and Yuejin 1988; Pigott 1941). High drilling fluid density has been proven to be very effective in improving the hole cleaning performance through the enhancement of cuttings suspension. However, increasing the drilling fluid density will also increase the hydrostatic downhole pressure and reduce the ROP, which will also raise the risk of hydrofracture and increase the cost due to low efficiency (Hopkin 1967).

2.5. Flow Velocity

Early researchr of hole cleaning problems recognized that the annular flow velocity as the most important factor (Hopkin 1967; Luo and Yuejin 1988; Pigott 1941). The researchers in the Tulsa University Drilling Research Projects (TUDRP) had conducted hundreds of cuttings transport tests and they found that in both vertical and horizontal drilling the increasing flow velocity always resulted in better hole cleaning performance (Hussaini and Azar 1983; Tomren et al. 1986). As for the flow regime, Tomren et al. (1986) pointed out that laminar and turbulent flow may both work effectively in vertical wells but the turbulent flow was found to be superior in horizontal wells. Luo and Yuejin (1988) attributed the better performance of turbulent flow to two reasons: (1) the flattened fluid velocity profile in turbulent regime provides higher velocity near the wall, (2) the eddies and swirls in turbulent flow enhance the erosion of the cuttings bed. To reach turbulent flow, one should either increase flow velocity or reduce the viscosity of the drilling fluid, which means low viscosity fluids are easier to be pumped in turbulent flow.

To achieve better hole cleaning performance in high inclination and horizontal wells, using low viscosity fluid in turbulent flow is always recommended (Bizhani et al. 2015; Leising and Walton 2002; Walker and Li 2000), however, in HDD the large annular space and limited pump pressure, as well as the high risk of hydro fracture all, imply that pumping drilling fluids, even water, in turbulent flow is impractical (Shu et al. 2015). Therefore, any investigation of hole cleaning performance in HDD should assume a relatively low annular velocity in laminar flow. Moreover, the hole cleaning performance in turbulent flow is independent of drilling fluid rheological properties, however, the cuttings transport in laminar flow should always consider the flow velocity together with drilling fluid rheological properties. The effect of flow velocity may also vary significantly when using different drilling fluids. In a study of cuttings transport in coiled tubing drilling, Leising and Walton (2002) used cuttings transport length which indicates the distance a cutting can be transported in the annulus to evaluate the hole cleaning performance. Due to the shear-thinning properties of drilling fluid, increasing flow velocity may cause a negative impact by reducing the drilling fluid's effective viscosity and increasing the settlement of the cuttings. Details of this research will be discussed in the next section. In addition, at extremely low flow velocity, the increase of velocity may lose its effectiveness. Zeng et al. (2018) conducted flow loop tests simulating cuttings transport in large-diameter HDD annulus. The flow velocity was varied from 0.01 m/s to 0.1 m/s, which was much lower than that of the ones used in any previous flow loop tests. The results showed that increasing the flow rate did not have a significant change to the cuttings bed when drill pipe rotation was absent.

2.6. Drilling Fluid Rheological Properties

As discussed above, the most effective variable, the flow velocity is restricted by either the pump capacity or the allowable annular pressure. Drilling fluid rheological properties, which are effective in improving cuttings transport and are much easier to be adjusted as well, is a good alternative. In this section, the most frequently used rheological models and the important conclusions from previous researches are introduced.

2.6.1. Rheological Models

Rheological models are used to fit the shear stress-shear rate relationships of the drilling fluids, and a proper selection of rheological model is the key to correctly evaluate the drilling fluid hole cleaning capacity. The most commonly used rheological models for drilling fluid in both petroleum industry and HDD industry are the Bingham plastic (BP) model, the power law (PL) model and the Herschel-Bulkley (HB) model (or yield-Power law model) (Hemphill et al. 1993; Kelessidis et al. 2006). Figure 2.6 shows the general shear stress-shear rate relationships of these three models. The equations and parameters of each model are presented in Table 2.2. For details about each model, the readers can refer to Ariaratnam et al. (2007).

Table 2.2 Rheological models

Models	Equations	Parameters
BP model	$\tau = YP + PV\gamma$	YP: yield point PV: plastic stress
PL model	$\tau = k\gamma^n$	k: consistency index n: flow behavior index
HB model	$\tau = \tau_y + k\gamma^n$	τ_y: yield stress k: consistency index n: flow behavior index

In summary, the BP model considers the viscoelastic property of drilling fluid but describes the shear stress/shear rate relationship as linear. The viscoelastic property indicates that the fluid possesses true yield stress due to their structural or elastic properties, which is important to drilling fluid cuttings suspension capacity. The yield stress is the minimum stress needs to initiate the flow within the fluid and is represented by a parameter called yields point (*YP*) in the BP model. *YP* is usually obtained from data measured at a high shear rate, which will lead to the inaccurate prediction of the low-shear-rate behavior (generally observed in the annulus) of the fluid (Hemphill et al. 1993; Nasiri and Ashrafizadeh 2010). The impact of using the BP model in the evaluation of drilling fluid hole cleaning capacity will be discussed later. The PL model only considers the shear-thinning property but does not include the viscoelastic property. Although the power-law model has been applied in HDD projects to predict annular frictional pressure loss and gives reasonable results when low shear rate viscometer readings were applied (Osbak 2011; Rostami et al. 2016), the missing of the viscoelastic property reduces the model accuracy when evaluating hole cleaning capacity drilling fluids in slow velocity.

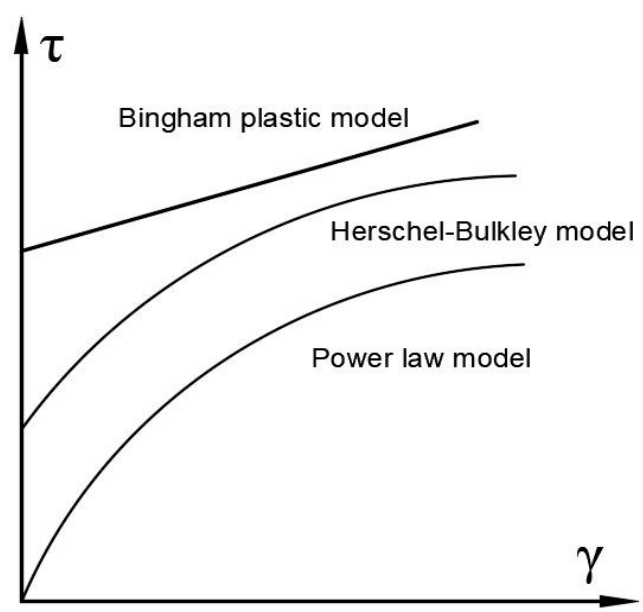


Figure 2.6 Shear stress-shear rate relationships of the three rheological models

The Herschel-Bulkley model, though has more complexity equation and calculation procedure due to its three-parameter feature, is the only one of the three commonly used models that consider both viscoelastic and pseudoplastic property of the drilling fluid. This model is also highly recommended by Kelessidis et al. (2006) when calculating pressure drop and velocity profile in the annulus.

2.6.2. Previous Investigations

At the early stage of drilling fluid hole cleaning capacity study, the BP model parameter plastic viscosity (*PV*) and yield point (*YP*), as well as the single rheological parameter apparent viscosity, were widely used. The apparent viscosity (sometimes called effective viscosity) is defined as the viscosity of an equivalent Newtonian fluid that would exhibit the same frictional pressure loss gradient as the non-Newtonian fluid, which is usually also measured at a high shear rate (Haciislamoglu and Langlinais 1990). Tomren et al. (1986) conducted one of the first laboratory experiments by using a 40 ft (12.2 m) flow loop section to study the major effective parameters. They found that in inclined annulus the low viscosity fluid in turbulent flow provided similar performance as the high viscosity fluid did in laminar flow. This interesting point was later explained by Pilehvari et al. (1999) that drill pipe rotation played a key role. According to their laboratory observation, the low viscosity fluid can easily pick up or roll the cuttings with low or no pipe rotation while in high viscosity fluid, the rotation of the drill pipe swirled the cuttings into the high-velocity region and the cuttings can be better suspended due to the higher viscosity.

Okrajni and Azar (1986) used the same facility as Tomren et al. (1986) but focused on the effects of the drilling fluid rheological properties. Based on the BP model and PL model they found that the higher the ratio of yield point to plastic viscosity (*YP*/*PV*) or the lower n value of PL fluids provided better cuttings transport. It was also found that high value of *YP* and *YP*/*PV* are more pronounced at low annular fluid velocity. They attribute the better hole cleaning performance to the flatter velocity profile caused by the high value of *YP*/*PV* or low value of n.

Although Bingham plastic model is the most commonly used rheological model in HDD industry (Ariaratnam et al. 2007), the accuracy of this model is always questionable. The true yield stress (TYS) is the minimum shear stress required to initiate the flow of the fluid which is represented by the *YP* in the Bingham model. This *YP* value is extrapolated from high shear rate (300 rpm and 600 rpm) readings obtained from Fann viscometer tests and often fails to be a good indicator for drilling fluid low shear rate behavior and is sometimes even inversely proportional to the TYS (Baumert et al. 2005; Beck et al. 1993; Hemphill et al. 1993). According to the results of the numerical modeling study of Chin (2001), for flow velocity range of 0.58 to 1.16 m/s, the general shear rate of drilling fluid is around 10 to 20 s^{-1} range which is more close to 6 rpm in the viscometer test. A correlation of the drilling fluid low shear rate range properties with hole cleaning was also provided by Becker et al. (1991). By studying hole cleaning performance of 15 different drilling fluids under different operational conditions and plotting cuttings concentration versus different parameters, Becker et al. (1991) found that 6 rpm Fann viscometer readings had the best correlation while the average annular shear rate, 3 rpm Fann viscometer readings and initial gel strength (10s) also correlated well.

However, in the study of rheological property and hole cleaning capacity of biopolymer drilling fluids, Powell et al. (1991) found that equivalent or higher 3 rpm readings did not reliably correlate to equivalent or higher suspension under static conditions. The low-shear-rate-viscosity (LSRV) and elastic modulus (G′) were found to correlate better to fluid suspension and transport capacity. The LSRV is the viscosity measured at 0.06 s^{-1} by advanced rheometer and is directly correlated with the TYS. The G′ is a measure of the elastic modulus of the fluid which defines the strength of the solid-like gel structure and can be measured by dynamic oscillatory rheometer (Beck et al. 1993). By testing Xanthan Gum fluid and HEC fluid under a wide range of shear rate, they found that although HEC exhibited a high value of 3 rpm readings, the shear stress would dramatically decrease when shear rate was further decreased while Xanthan Gum fluid still showed measurable shear stress as the shear rate approached to zero (high LSRV). The high LSRV and TYS not only provided better suspension to cuttings at static suspension tests but also provide flatter velocity profile.

The flattened velocity profile has been well documented to provide better cuttings transport, especially in low velocity and highly inclined wells. A schematic of flattened velocity profile and non-flattened velocity profile is presented in Figure 2.7.

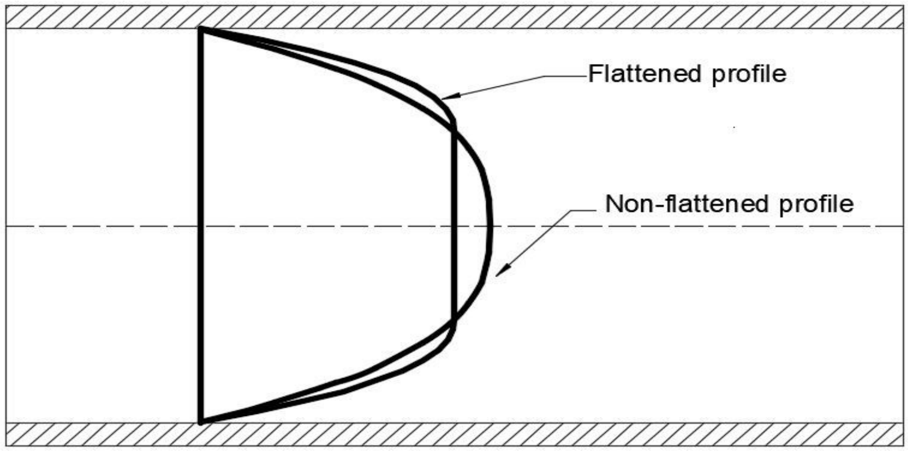


Figure 2.7 Flattened and non-flattened velocity profiles

The features and benefits of flattened profile can be summarized as (Beck et al. 1993; Dzuy and Boger 1983; Leising and Walton 2002; Powell et al. 1991; Zamora et al. 1993):

(1) Due to the existence of TYS, there will be an unsheared solid plug region where the shear stress is less than the TYS. The low or near zero shear rate in this region will give the high fluid viscosity which is of significance in suspending cuttings.

(2) Adjacent to the borehole wall and the pipe wall, the shear stress exceeds the TYS, and the fluid in these layers start to be sheared and become thinner due to the shear-thinning property. The high shear stress and high shear rate in these regions will cause higher shear stress on the cuttings bed surface to enhance the bed erosion. The Experimental observation from Powell et al. (1991) had shown that cuttings near the wall tended to migrate to the center of the mainstream where the velocity gradient is low and the viscosity is high.

(3) Higher TYS and a higher degree of shear-thinning properties will both widen the plug region and limit the high shear rate region. Moreover, a higher degree of shear-thinning (lower 'n' value in the power law model) will also lower the pump pressure and increase allowable pump rate to further enhance the cuttings transport. In HDD wellbores, which are quite sensitive to annular pressure, this property is more desired.

Based on the above discussion of the flatter velocity profile we can understand why the previous researches all attribute the better cleaning performance of fluids with higher YP/PV to flatter velocity profile (Becker et al. 1991; Okrajni and Azar 1986). However, the accuracy of the Bingham plastic model may impact the reliability of this index, especially at low flow rate situation in HDD. Therefore, the applicability of this simple and widely used method should be verified when used in drilling fluid hole cleaning capacity evaluation in the HDD annulus. For the prediction of the velocity profile in the annulus, Kelessidis et al. (2006) proposed an approach based on HB model which was proven to be more accurate in describing non-Newtonian drilling fluid rheological and hydraulic behaviors in laminar flow (Hemphill et al. 1993). Ofei (2016) also adopted HB model in numerical simulation of cuttings transport in eccentric horizontal wells. Therefore, HB model which is rarely used in cuttings transport analysis may be a good alternative to the frequently used conventional models.

2.7. Drill Pipe Rotation

In the early stage of hole cleaning studies, the effect of the drill pipe rotation was underestimated since the pipe was thought to rotate along its axis (Iyoho 1980; Peden et al.

1990). Sanchez et al. (1997) pointed out that the drill pipe does not only rotate along its axis but also has orbital motion. According to their observation in the flow loop tests, the rotation along the axis produced pseudo-helical flow which showed minor improvement in cuttings transport while the orbital motion exhibited a significant effect by (1) mechanically agitating the cuttings in the cuttings bed into the mainstream and (2) exposing the cuttings in the narrow gap under the drill pipe to the high-velocity flow fluid. In addition, the effect of pipe rotation was found more significant for high viscosity fluids at a low flow rate. This confirms the statement mentioned earlier that the high viscosity fluid in laminar flow can provide hole cleaning performance as good as low viscosity fluid in turbulent flow due to the function of drill pipe rotation (Pilehvari et al. 1999). Similar results were also reported by (Duan et al. 2008).

In HDD industry, a series laboratory flow loop tests were conducted by Zeng et al. (2018) to simulate cuttings transport in large diameter HDD annulus. One of their results showed that the increase of flow rate or changing fluid properties showed the minor effect on cuttings bed without drill pipe rotation. After introducing the pipe rotation, a remarkable improvement in bed erosion and cuttings transport was observed. Only, in this case, were the flow rate and drilling fluid rheological properties found to be functional. Since the flow rate is significantly lower (0.01 m/s to 0.1 m/s) than that of the ones in the previous experiments, which is closer to the real annular flow velocity in HDD, the results reveal the major different of cuttings transport between HDD and traditional oil and gas wells: at extremely low flow velocity, the drill pipe rotation plays a more important role in cuttings bed erosion instead of the drilling fluid which function more as a carrying medium.

2.8. Conclusions

This chapter provided a review on hole cleaning studies in HDD as well as inclined and horizontal oil and gas wells. Cuttings transport pattern and simulation models in horizontal wells are also discussed. The factors affecting the cuttings transport in horizontal wells are introduced based on their effectiveness and controllability in HDD practice. The most effective and controllable factors, flow velocity, drilling fluid rheological properties and drill pipe rotation were specifically discussed. These factors are not independent. Instead, they are all highly dependent on each other. Based on the discussions provided above several conclusions can be made:

(1) Compared to traditional inclined and horizontal oil and gas wells in the petroleum industry, the wells in HDD have several unique features like large borehole diameter and high sensitivity to annular pressure, which restricted the annular flow velocity to be in laminar flow at an extremely low-velocity range. This may change the priority of the influential factors, the criteria for cuttings transport modeling as well as evaluation of the drilling fluid hole cleaning capacity.

(2) The rheological parameters used to evaluate drilling fluid hole cleaning capacity vary from basic *YP*, *PV*, PL n value and apparent viscosity to LSRV and G' which are obtained by using high precision apparatus. However, they all suggest that flatter velocity profile is good for hole cleaning in horizontal wells especially at low flow rate.

(3) Although drill pipe rotation has been proved helpful in improving hole cleaning performance in horizontal oil and gas wells, its importance may be further emphasised in HDD. Since extremely low flow velocity significantly diminished

sweeping (erosion) capacity of drilling fluid, the disturbance (erosion) to the cuttings bed highly depends on the drill pipe rotation.

For future researches, three suggestions can be offered:

(1) New flow pattern and cuttings transport model in HDD annulus need to be developed based on HDD's unique feature like large diameter and low flow velocity.

(2) New method needs to be developed to evaluate drilling fluid hole cleaning capacity in HDD annulus, especially the suspension and carrying capacity. Herschel-Bulkley model is recommended due to its higher accuracy in rheological and hydraulic behavior prediction than conventional BP and PL models.

(3) Large-scale flow loop tests need to be conducted to simulate cuttings transport in HDD annulus and verify the flow patter, cuttings transport model as well as the drilling fluid evaluation method.

Chapter 3: Rheological Properties of Clay-Base Drilling Fluids and Evaluation of Their Hole Cleaning Performances in Horizontal Directional Drilling[1]

3.1. Introduction

Horizontal directional drilling (HDD) is a cost-effective trenchless construction technology, which is generally used to install pipelines and underground utilities with minimal surface disruption (Ariaratnam et al. 2007). However, in the HDD drilling process, hole cleaning is always one of the most common and costly problems, which is also an issue in conventional oil well drilling (Osbak 2012; Pilehvari et al. 1999). Insufficient hole cleaning may cause a series of costly problems, including increasing torque and drag requirement, inducing high annular circulating bottom hole pressure, and even causing mechanical stuck pipe (Pilehvari et al. 1999). A drilling fluid is a multi-functional fluid circulated in the drilling assembly and annulus. The main functions of the drilling fluid can be summarized as (1) suspension and removal of cuttings from the borehole; (2) lubricating the bottom hole assembly; (3) hydraulic jetting of cutting and fracturing soils and rocks; (4) driving the mud motor if applied; (5) maintaining the borehole stability; (6) cooling the downhole tools and electronics (Ariaratnam et al. 2007; Shu et al. 2014). Depending on the type of well drilling, one or more of these functions may take precedence over the other (Caenn and Chillingar 1996). In horizontal drilling, the cuttings do not fall opposite to the

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[1] This chapter has been submitted the Journal of Pipeline Systems Engineering and Practice and is under review.

direction of fluid flow, as is the case in vertical well drilling, and the mud's capability to suspend cuttings is significantly reduced (Sifferman and Becker 1992). As such, the function of cleaning and carrying capacities becomes more critical for the drilling fluid in HDD (Sifferman and Becker 1992; Caenn and Chillingar 1996).

The factors affecting the hole cleaning performance in oil and gas wells have been widely investigated and can be classified into three groups: (1) fluid parameters, such as flow velocity, mud density, and rheological properties; (2) cutting parameters, such as cuttings density, dimension, and concentration; (3) operational parameters, which consist of hole inclination (from vertical), rate of penetration as well as drill pipe rotation and eccentricity in the annulus (Bilgesu et al. 2007).

Pigott (1941) conducted one of the first researches on the flow of drilling fluid in pipes, wellbores, and mud pits. He calculated the slip velocity using Stokes's law for the laminar flow and Rittinger's law for the turbulent flow of particles and concluded that high velocity and density are useful for lifting cuttings, but high viscosity is not desirable as it will raise pumping pressures and decrease the velocity.

The University of Tulsa conducted a series of tests to investigate the effects of various factors on the hole cleaning performance. The researchers found that for vertical wells, fluid annular velocity has a major effect on the carrying capacity of the drilling fluid, which is significant, especially at low viscosities (Hussaini and Azar 1983). For high angles of inclination, turbulent flow is preferred and the cleaning performance of the fluid in turbulent regime is independent of the drilling fluid rheological properties (Okrajni and Azar 1986). The positive drill pipe eccentricity in highly inclined and horizontal wells accelerates the build-up of the cuttings bed (Tomren et al. 1986). The drill pipe rotation also affects the hole cleaning significantly in highly inclined wells at low flow rates, especially when high viscosity drilling fluids are used, due to the mechanical agitation of cuttings on the low side of the annulus (Sanchez et al. 1997).

Despite the number of known factors that can affect hole cleaning performance in the drilling operation, only a few of them are controllable. Based on the results from the previous studies, it is commonly agreed that increasing flow rate and drilling fluid density is the most effective way of improving the cleaning capacity of drilling fluid; however, there are several limitations to increasing these two parameters (Becker et al. 1991). A high flow rate requires higher pump capacity and will cause higher annular pressure losses and consequently, higher dynamic bottom hole pressure, which may lead to instability, or even hydrofracture, of the borehole (Baumert et al. 2005; Ariaratnam et al. 2007; Staheli et al. 2010). Although increased fluid density can improve the buoyant force to help suspend the cuttings, it will also increase the hydrostatic pressure and, as a result, lower the rate of penetration (Azar and Sanchez 1997). Other factors, such as well inclinations, size of cuttings, and drill pipe eccentricity are either less effective or hard to control. Rheological properties of drilling fluid, although not as effective as fluid velocity and density, are more manageable (Becker et al. 1991; Adari et al. 2000).

There are three rheological models commonly used to describe the rheological behavior of bentonite mixtures: namely the Bingham plastic (BP) model, the power law (PL) model, and the Herschel-Bulkley (H-B) model (Baumert et al. 2005) (Figure 3.1). The BP model indicates that shear stress linearly increases against shear rate, which cannot show the shear-thinning property of drilling fluids and will overestimate the shear stress at a low shear rate as well as the yield point (Ariaratnam et al. 2007). The power law model can describe the shear-thinning behavior. However, it does not incorporate yield stress, which is observed in most drilling fluids. (Hemphill et al. 1993). Complex rheological models result in more complicated engineering calculation procedures, but the complexity brings more accuracy in predicting the behavior of drilling fluids (Kelessidis et al. 2006). Therefore, the three-parameter H-B model, which exhibits both shear-thinning and yield stress properties, is considered a compromise between the accuracy and the simplicity (Hemphill et al. 1993; Kelessidis et al. 2006).

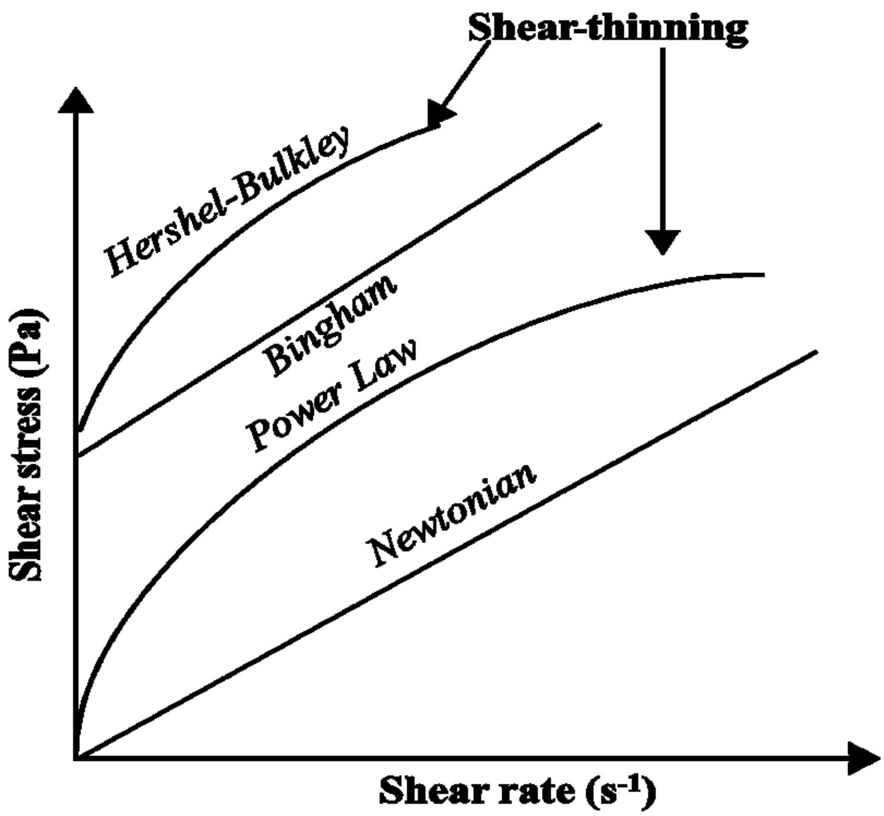


Figure 3.1. Shear stress versus shear rate relationships of various rheological models

A parameter based on the BP model, yield point to plastic viscosity ratio (*YP*/*PV*), was first introduced by Hussaini and Azar (1983) as an indicator of drilling fluid carrying capacity of solids. Cuttings transport experiments using 15 drilling fluids of different rheological properties indicated that higher *YP*/*PV* improves cuttings transportation at all angles of inclination and the effect is more significant at low fluid velocity (Becker et al. 1991). The researchers attributed this improvement to the flatter velocity profile caused by higher value of *YP*/*PV* (Okrajni and Azar 1986; Becker et al. 1991). The flatter velocity profile has been widely proved to be good at particle transportation due to its low shear rate and high viscosity core region (plug region) to suspend cuttings, as well as the high shear rate and low shear viscosity region near the wall to erode the cuttings bed (Beck et al. 1993; Leising and Walton 2002; Nguyen and Boger 1992; Shu et al. 2015; Ziaee et al. 2015). However, *YP* and *PV* values are generally estimated by using high shear rate readings (300 and 600 rpm) of a Fann viscometer, which are higher than the actual shear rates observed in the HDD annulus (Baumert et al. 2005; Ariaratnam et al. 2007). In addition, the width of the plug region (plug width) is proportional to the magnitude of the true yield stress (TYS) or yield stress, which is usually lower than the *YP* extrapolated from 300 and 600 rpm readings and inversely proportional to the pressure gradient (frictional pressure loss) in the fluid, which is quite sensitive to rheological parameter selections (Beck et al. 1993). Thus, using the *YP*/*PV* ratio, which is estimated using the inexact rheological model and measurements under excessive shear rate to indicate the flatness of the velocity profile, should be further examined.

Since the hole cleaning process is directly related to the hydraulic behavior of drilling fluid, which depends on the drilling fluid rheological properties, by introducing the hydraulic parameters such as frictional pressure loss (ΔP), fluid shear stress at the wall (τ_w), and plug width (h), the author suggests using these parameters to indicate how the rheological parameters will influence the cleaning capacity of the drilling fluid. The hole cleaning capacity is divided into two main components: the carrying capacity which indicates the fluid's capacity to suspend cuttings, and the sweeping capacity which describe the capacity of eroding the cuttings bed.

In this study, water-based drilling fluids with different bentonite concentrations were tested in a six-speed rotational viscometer to obtain their shear stress and shear rate relationships. Then, the conventional BP model and the H-B model were both used to fit the measured data and describe the flow behavior of the fluids. The accuracy of the BP model and H-B model for predicting flow behavior of the fluids were compared and discussed. Based on H-B model, the hydraulic parameters h, τ_w, and ΔP were calculated by using the H-B model procedure suggested by API Recommended Practice 13D (API RP 13D 2010). The effect of the bentonite concentration on the rheological properties of the drilling fluids and their associated hydraulic parameters have been investigated to evaluate the potential hole cleaning capacity of water-based bentonite drilling fluids in HDD annulus.

3.2. Methodology

The rheological models can describe the shear-stress/shear-rate relationship of each drilling fluid and be used to predict its hydraulic behavior in the annulus, which is directly related to hole cleaning performance. Based on the H-B model, the hydraulic parameters of the drilling fluid in the annulus are calculated to better understand how the rheology of the drilling fluid effects the hole cleaning procedure and allows us to build a new evaluation system of the drilling fluid hole cleaning capacity. The functions and mechanisms of hydraulic parameters ΔP, τ_w, and h are explained. The effects of the bentonite concentration on the value of YP/PV (based on the BP model) and ΔP, τ_w, and h (based on the H-B model) are calculated and compared.

3.2.1. Rheological Models

Most drilling fluids are non-Newtonian fluids (Ariaratnam and Beljan 2005), especially when bentonite and polymers are added. The Bingham plastic model, the power law model, and the Herschel-Bulkley model are the conventional rheological models to describe the behavior of the drilling fluid (Ariaratnam and Beljan 2005). Due to the zero-yield stress feature of the power law model, which is important in hole cleaning, only the BP and the H-B model were considered in this research.

3.2.1.1. Bingham Plastic Model

The Bingham plastic (BP) model is given as a function of the yield point and the plastic viscosity. It describes a linear relationship between shear rate (γ, s^{-1}) and shear stress (τ, Pa) and can be expressed as:

$$\tau = YP + PV\,\gamma \qquad (3\text{-}1)$$

where YP is the yield point (Pa) which is minimum stress required to initiate flow in the fluid and PV is the plastic viscosity (PV, Pa·s) which is defined as the shear stress in excess of the yield point that will induce unite rate of shear. Based on API RP 13D, the two parameters in Eq. (3-1) can be obtained from API rotational viscometer readings at 300 rpm (θ_{300}) and 600 rpm (θ_{600}):

$$PV = \theta_{600} - \theta_{300} \tag{3-2}$$

$$YP = \theta_{300} - PV \tag{3-3}$$

Previous studies suggested that higher the *YP*/*PV* ratio, the better the hole cleaning performance of a drilling fluid would be (Hussaini and Azar 1983; Okrajni and Azar 1986). However, as it can be seen from Eqs. (3-2) and (3-3) the BP model only considers fluid rheological behavior at high shear rates and will usually fail to simulate the low shear rate behavior of fluid, which is more representative for the flow in the annulus (Hemphill et al. 1993). In HDD projects, the maximum spindle rotating speed varies from 100 rpm to 260 rpm depending on the size of rigs (Ariara tnam et al. 2007); thus, the current method of using the BP model should be questioned.

3.2.1.2. Herschel-Bulkley Model

The Herschel-Bulkley (H-B) model describes a non-linear relationship between shear stress and shear rate using the yield stress τ_y (Pa), as same as the *YP* in the Bingham plastic model, is the critical stress required to initiate flow in the fluid, the consistency index k ($Pa \cdot s^n$) which describe the viscosity of the fluid only in dynamic flow state, and the flow behavior index n that indicates the degree of the shear-thinning behavior of the fluid. The mathematical formulation of the H-B model is defined by the Eq (3-4):

$$\tau = \tau_y + k\,\gamma^n \tag{3-4}$$

API RP 13D recommends two different procedures to solve the H-B parameters known as the measurement method and the numerical method.

As for the measurement method, the three parameters can be determined by using Eqs.(3-5) to (3-7).

$$\tau_y = 2\ \theta_3 - \theta_6 \tag{3-5}$$

$$n=3.32\ \log\left(\frac{\theta_{600}-\tau_y}{\theta_{300}-\tau_y}\right) \tag{3-6}$$

$$k=\frac{\theta_{300}-\tau_y}{511^n} \tag{3-7}$$

A more accurate characterization of the fluid rheological behavior can be achieved by using the numerical method, where a value of n needs to be assumed initially and, after that τ_y and K can be determined by using the Eqs. (3-8) and (3-9):

$$\tau_y=\frac{\sum \tau_i \times \sum \gamma_i^{2n} - \sum \tau_i \gamma_i^n \times \sum \gamma_i^n}{N\times \sum \gamma_i^{2n} -(\sum \gamma_i^n)^2} \tag{3-8}$$

$$k=\frac{N\times \sum \tau_i \gamma_i^n - \sum \gamma_i^n \times \sum \tau_i}{N\times \sum \gamma_i^{2n} -(\sum \gamma_i^n)^2} \tag{3-9}$$

where N is the number of data sets which is 6 in our case, and i varies from 1 to 6.

The error (Err) is determined by:

$$Err=\tau_y\times \left(\sum \gamma_i^n \times \ln(\gamma_i)\right) +K\times \left(\sum \gamma_i^{2n} \times \ln(\gamma_i)\right) -\left(\sum \tau_i , \times \ln(\gamma_i)\right) \tag{3-10}$$

The assumed value of n is changed and steps (4) and (5) are repeated until the Err is less than the recommended value of 0.05.

3.2.2. Hydraulic Behaviors

3.2.2.1. Velocity Profile and Suspension Capacity

For a flow in a concentric annulus, to simplify the model calculations, the annulus can be approximated by a slot of gap H (m) (Kelessidis et al. 2006):

$$H=\frac{d_{hyd}}{2}=\frac{d_h-d_p}{2} \qquad (3\text{-}11)$$

where d_h is the borehole diameter (m), d_p is the outer diameter (m) of the drill pipe, and d_{hyd} is the hydraulic diameter (m).

The velocity profile in the annulus is shown in Figure 3.2. For the flow of a yield stress fluid, there will be an unsheared plug (rigid core) region of the velocity profile where the shear stress is less than the yield stress of fluid (Zamora et al. 1993; Kelessidis et al. 2006). Here, the width of the rigid core is defined as the plug width (h_p) which is used to indicate the flatness of the velocity profile.

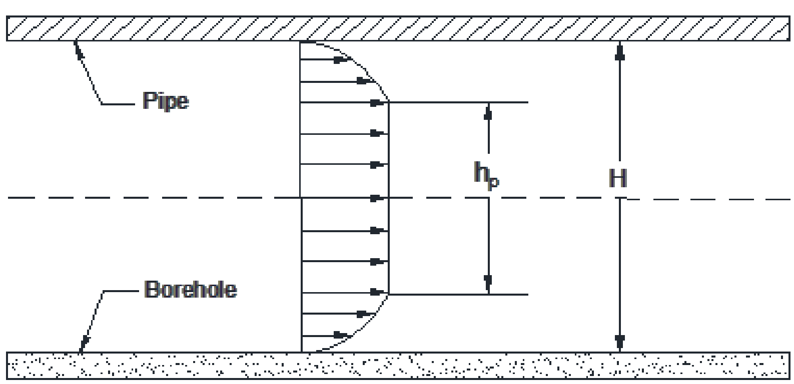


Figure 3.2. Velocity profile of drilling fluid in the annulus

Based on the Herschel-Bulkley model, the wall shear stress (τ_w, Pa) and the annular frictional pressure loss (ΔP, Pa/m) were calculated using the recommended procedure from API RP 13D. The plug width, h_p (m), was then calculated by using the Eq. **Error! Reference source not found.**.

$$h_p = \frac{2\tau_y}{\Delta P} \qquad (3\text{-}12)$$

In order to compare the plug width under different conditions, a normalized plug width, h (%), (i.e. percentage of the total annular gap, H, occupied by the plug zone; $= \frac{h_p}{H} * 100$) will be used.

Since the fluid drag force due to velocity will be diminished as the inclination increases (Okrajni and Azar 1986), especially in horizontal drilling, the fluid velocity that is high enough to prevent formation of cuttings bed is hard to reach, and the function of the plug zone width becomes more significant. Due to the yield stress and the shear-thinning properties of drilling fluid, the plug region has low to zero shear rate which results in extremely high local viscosity. The high viscosity can provide good suspention to the cuttings, extends the distance that cuttings can be transported before settling down and prevents or slows down the formation of the cuttings bed (Leising and Walton 2002). This is also supported by the laboratory flow loop tests conducted by Zamora et al. (1993), during which sand particles were observed to evenly distribute and fully suspend across the flat velocity profile. The suspension capacity of drilling fluids depends on how much weight of cuttings it can suspend at both static state (when the pump stops) and dynamic state (when the fluid flows). Beck et al. (1993) and Powell et al. (1991) found that high low-shear-rate properties like higher value of low-shear-rate-viscosity (LSRV), true yield stress (TYS) and elasticity (storage modulus (G′) and loss modulus (G″)) can provide better suspension to the cuttings at both static and dynamic states. In addition, high TYS and good shear-thinning properties can also widen the unsheared plug region (plug width) to occupy more areas in the annulus and provide suspension (Leising and Walton 2002). Therefore, in this study, the yield stress (τ_y) obtained from H-B model is used to approximate the TYS and the nomalized plug width (h_p) is used to indicate the flatness of the velocity profile. These two parameters are used together to indicate the suspension capacity of the tested drilling fluid.

3.2.2.2. Bed Erosion and Sweeping Capacity

As mentioned in Chapter 2, to initiate the bed erosion, the mobilizing forces are supposed to surpass the resistive forces. The main force to initiate particle movement is the fluid drag force (Ramadan et al. 2003). The fluid drag force is directly related to the wall shear stress (τ_w, Pa) which is the shear stress at the mud-bed interface (Bizhani et al. 2015). The high wall shear stress is useful for removing the cuttings from the stationary bed and bringing them up to the higher velocity and viscosity mainstream in the plug region, thus providing better hole cleaning performance (Leising and Walton 2002; Zamora et al. 1993). The wall shear stress, τ_w, is directly proportional to the annular frictional pressure loss, which is the function of the fluid flow velocity and rheological parameters (τ_y, k and n) and can be calculated by using the procedure recommended by API RP 13D.

The high frictional pressure loss caused by increasing flow velocity has been widely proved to be effective in improving cuttings bed erosion as well as enhancing the hole cleaning performance (Becker et al. 1991; Khatibi et al. 2018; Saasen 1998). However, the high frictional pressure loss induced by high drilling fluid rheological properties seems to provide opposite effect. The phenomenon was reported by lots of researchers that high viscosity fluids usually need to be pumped at higher flow velocity to achieve the same effect of bed erosion when using lower viscosity fluids (Bizhani et al. 2016; Duan et al. 2009; Leising and Walton 2002; Walker and Li 2000). At the same flow velocity, the high viscosity fluid can already induce higher wall shear stress or drag force on the cuttings bed but higher velocity is still required to provide even higher drag force to erode the bed, which indicates a lower efficiency in bed erosion or low sweeping capacity. Bizhani and Kuru (2018a) gave a reasonable explanation that there should be an additional resistive force due to the viscoelasticity characteristics of the high viscosity fluid: According to Bird et al. (1987), in viscoelastic fluid, the normal stress differences are not zero due to the anisotropies developed in the molecules which will create a compressive force in the vertical direction to increase the resistive forces (Figure 3.3). By testing the critical bed erosion velocity of water and polymer fluids, Bizhani and Kuru (2018a) found the minimum flow rate required for bed erosion will increase significantly as more polymers were added, which is due to the higher compressive force induced by high viscoelasticity in polymer drilling fluids. Since water-based bentonite drilling fluids also show viscoelastic characteristics (high value of LSRV and YTS), this additional resistive force may also exist in bentonite drilling fluids. In some early tests Bizhani et al. (2015) also found consistent results that critical wall shear stress needed to initiate the cutting movement on the bed will decrease as the consistency index, k, and flow behavior index, n, decrease.

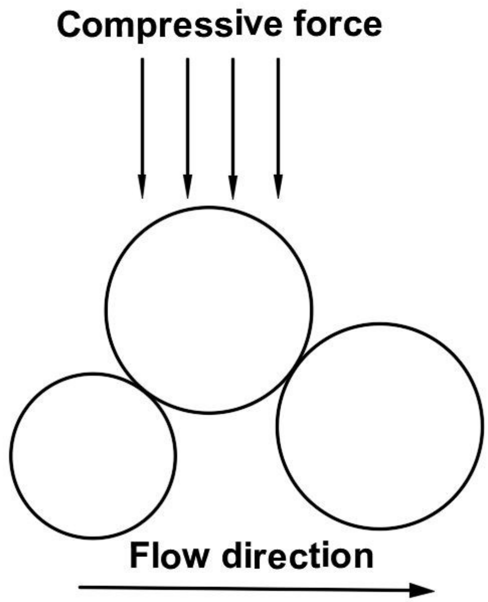


Figure 3.3 Compressive force caused by the normal stress difference in viscoelastic fluids

Moreover, the high frictional pressure loss caused by fluid rheological properties may also lead to safety concerns. When drilling fluid flows in the annulus, the total borehole pressure consists of two parts: the hydrostatic pressure and the frictional pressure loss (Ariaratnam et al. 2007). Hydrostatic pressure is due to the weight of the fluid column and the frictional pressure loss is caused by the internal resistance of the fluid (Osbak 2011). The increase of frictional pressure loss will lead to a rise in the total annular pressure which will either increase the risk of hydrofracture or limit the allowable flow rate.

3.3. Materials and Experimental Procedure

3.3.1. Materials

In this study, the most commonly used water-based bentonite drilling fluid was selected as the test fluid. Bentonite is a natural clay that consists of a high percentage of montmorillonite (Ariaratnam and Beljan 2005). An industrial bentonite, which is designed for use in the mineral exploration, the water well drilling, and the other directional drilling operations is selected. This bentonite is odorless, light tan to gray dry powder with a specific gravity of 2.45 to 2.55. The methylene blue adsorption test (MBAT) was conducted to determine Cation Exchange Capacity (CEC) of the bentonite sample (Cokca and Birand 1993). The CEC and Atterberg limits of the bentonite are listed in Table 3.1.

Table 3.1. Physico-chemical properties of tested bentonite

Cation exchange capacity (meq/100g)	Atterberg limits	
	Plastic limit	Liquid limit
209.8	54%	515%

3.3.2. Experimental Procedure

Since excessively high density of drilling fluid will cause a low rate of penetration and a high cost due to high (pumping) energy consumption (Azar and Sanchez 1997), bentonite concentrations of 1% to 5% (10 kg/m^3 to 50 kg/m^3) are commonly accepted in the industry. Since preparation has a significant influence on the properties of drilling fluid, all samples were strictly prepared under the same conditions and using the same procedure (Benna et al. 1999).

To prepare the sample, a percentage of bentonite by weight (1% to 5%, with increments of 0.5%) was mixed with 350 mL distilled water by a Hamilton Beach HMD200 Series Single Spindle mixer (Figure 3.4a) under high speed (18000 rpm) for 20 minutes. It was found that even a small change in the fluid temperature would cause a noticeable difference in the rheological test results. Thus, after the mixing was done, the containers of the specimen fluids were placed in water to cool the drilling fluid down to the room temperature (20°C).

The rheological properties of clay base drilling fluids are time-dependent (Gray and Darley 1980) and they build a gel structure during the cooling process. Therefore, before doing any further tests, the drilling fluid samples were re-agitated using the same mixer. This procedure was limited to 1 minute to avoid any significant rise in the fluid temperature due to high-speed shearing.

Figure 3.4. Testing apparatus (a) Hamilton Beach HMD200 Series Single Spindle mixer(b) Fann 35A viscometer

Following the instruction of the API Recommended Practice 13B-I, rheological characterization tests were conducted at six speeds: 600, 300, 200, 100, 6, and 3 rpm, using Fann 35A viscometer (Figure 3.4b). We have prepared and tested 3 samples at each bentonite concentration. The average of the 3 test results were used for further calculations and analyses.

3.4. Results

3.4.1. Viscometer Test Results

The results of the Fann 35A viscometer measurements of drilling fluids with 9 different bentonite concentrations are plotted in the rheograms (shear stress vs. shear rate) as shown in Figure 3.5. Each curve in Figure 3.5 corresponds to an average of the 3 measurements of fluid properties at a specific bentonite concentration. The results indicate that all the fluids have yield stress and shear-thinning characteristics, which imply that the rheological characteristics of the water-based bentonite drilling fluids can be described by the Herschel-Bulkley model. It was also noted that both the yield stress, τ_y, and the apparent viscosity at each shear rate increase as the bentonite concentration increases.

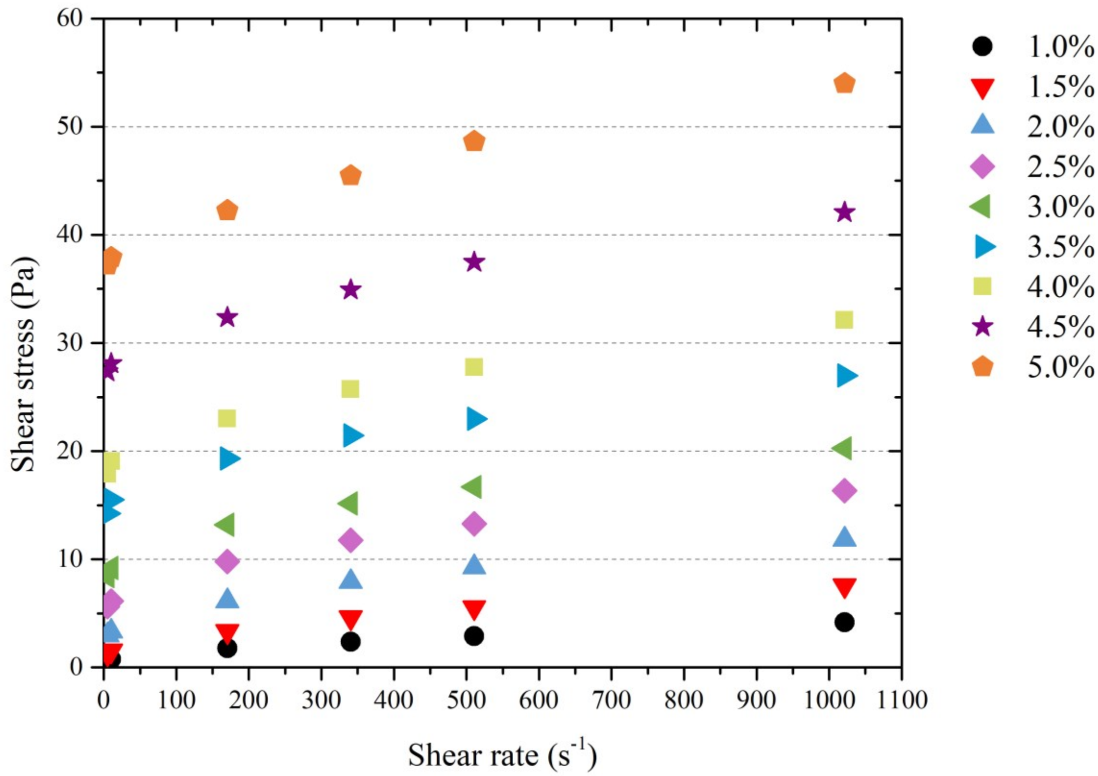


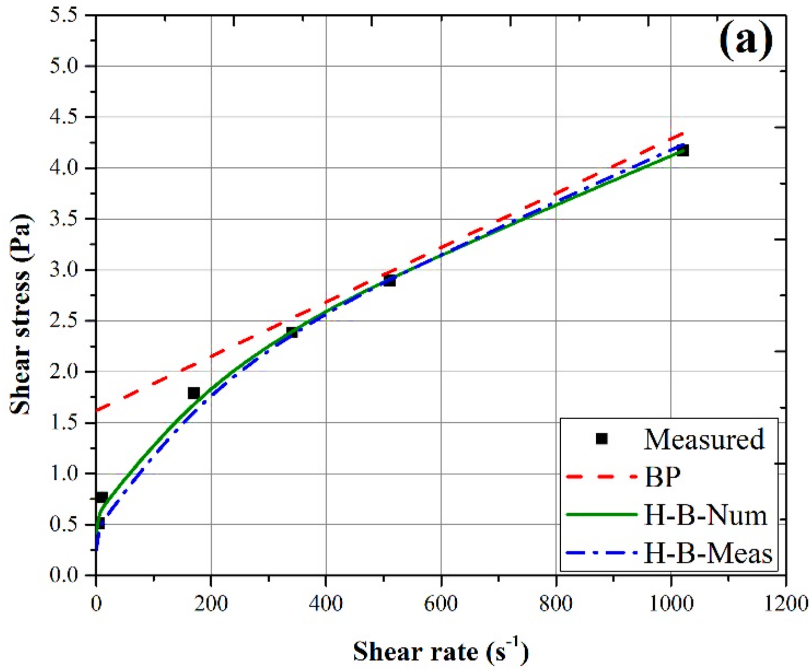
Figure 3.5. Rheograms of drilling fluids with different bentonite concentrations

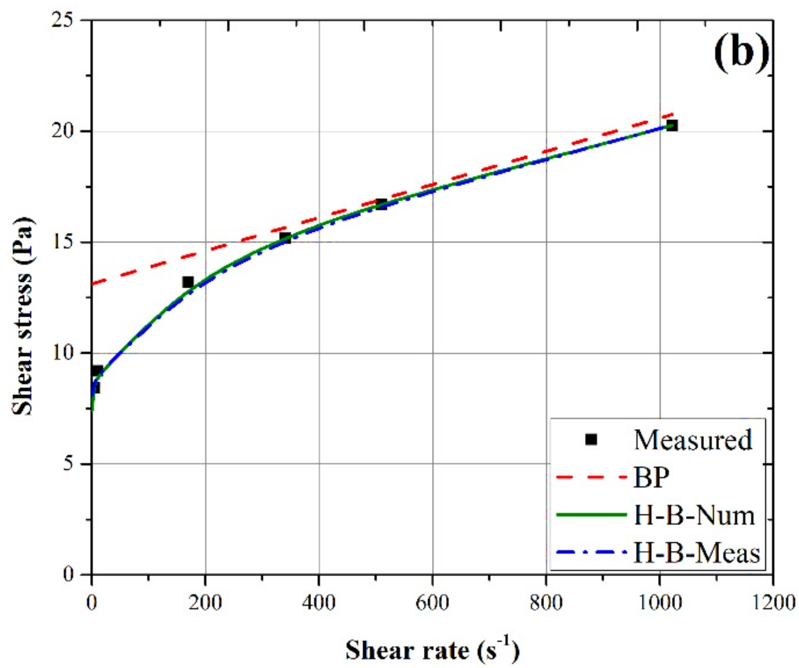
3.4.2. Prediction of Drilling Fluid Rheological Parameters Using BP and H-B Models

The BP model and the H-B model were both used to fit the measured data. For the H-B model, API recommended measurement method (H-B-Meas) and the numerical method (H-B-Num) were both used to predict the rheological behavior of the drilling fluids. For each concentration, predicted shear stress-shear rate relationship together with measured data are plotted on one graph, and some (1%, 3%, and 5% bentonite concentrations) are presented in Figure 3.6.

Figure 3.6.a to Figure 3.6.c indicate that, although the BP can give a good prediction at a high shear rate (300 to 600 rpm), it overestimates the shear stress at the low range of shear

rate, and gives a yield point which is much higher than the actual yield stress. For the H-B model, both numerical techniques and the measurement method can capture the profile of the shear stress-shear rate behavior well and give better predictions across all ranges of the shear rates compared to the BP model.


(a)
Shear stress (Pa)
Shear rate (s-1)
Measured
BP
H-B-Num
H-B-Meas
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
0
200
400
600
800
1000
1200


(b)
Shear stress (Pa)
Shear rate (s-1)
Measured
BP
H-B-Num
H-B-Meas
0
5
10
15
20
25
0
200
400
600
800
1000
1200

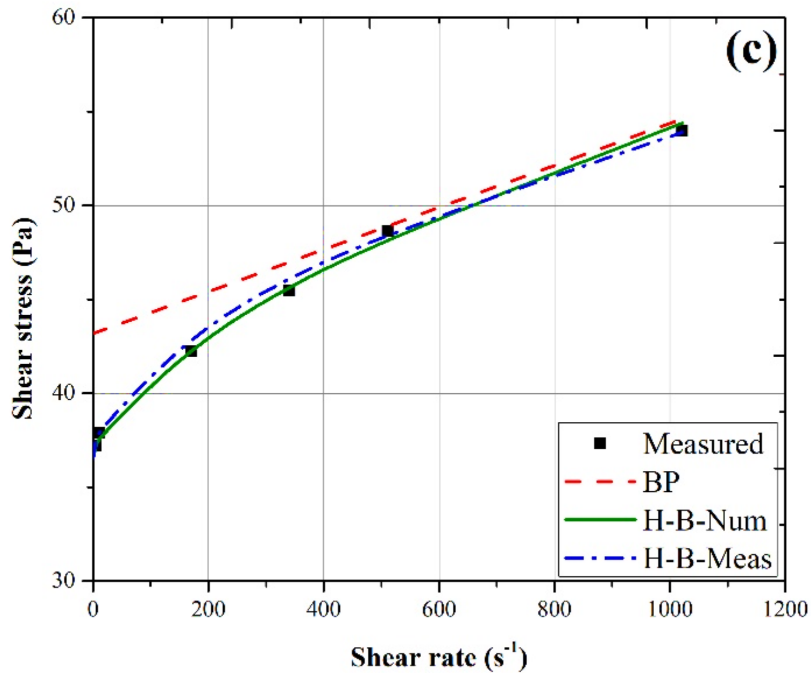


Figure 3.6. Comparison of the experimental shear stress vs shear rate data with the predictions from BP and H-B models (a) 1% bentonite drilling fluid (b) 3% bentonite drilling fluid (c) 5% bentonite drilling fluid

To quantify the goodness of fit (*GoF*) of different models and methods, the coefficient of determination (R^2) is commonly used (Kelessidis et al., 2006). But Kelessidis et al. (2006) observed that using only R^2, which is designed for linear functions, is not suitable for non-linear rheological models of drilling fluids since the two different sets of parameters may give similar values of R^2, making it hard to determine the better rheological parameter. Therefore, Kelessidis et al. (2006) recommended to use another indicator, best index value (*BIV*), for determining the quality of the model prediction of the non-linear functions.

$$R^2 = 1 - (\sum_i y_i - \hat{y_i})/(\sum_i \hat{y_i} - \bar{y}) \tag{3-13}$$

$$BIV = (\sum_i \widehat{y_i} - \bar{y})/(\sum_i y_i - \bar{y}) \quad (3\text{-}14)$$

where y_i are the measured quantities, $\widehat{y_i}$ are the predicted quantities, and $\bar{y}$ are the measured average values. The range of R^2 varies from 0 to 1, while the *BIV* range can go beyond 1. The closer the value of R^2 and *BIV* to 1, the better the *GoF* of the rheological model. If the *BIV* is smaller than 1, the model under-predicts the rheological behavior, while a value higher than 1 indicates the over-prediction.

Table 3.2. Rheological parameters calculated by BP model

Bentonite percentage	**BP parameters and *GoF***			
	YP (Pa)	*PV* (Pa·s)	R^2	*BIV*
1.0%	1.5162	0.0025	0.7698	0.6900
1.5%	3.2718	0.0040	0.6599	0.6560
2.0%	6.3042	0.0050	0.5150	0.6255
2.5%	9.5760	0.0060	0.5212	0.6071
3.0%	12.2892	0.0070	0.6075	0.6066
3.5%	17.7954	0.0078	0.6702	0.6214
4.0%	21.9450	0.0085	0.6156	0.6359
4.5%	30.8028	0.0090	0.6143	0.6581
5.0%	40.4586	0.0105	0.6362	0.6673

Table 3.3. Rheological parameters calculated by H-B model (measurement method)

Bentonite percentage	**H-B (measurement method) parameters and *GoF***				
	τ_y (Pa)	k (Pa·s^n)	n	R^2	*BIV*
1.0%	0.239	0.072	0.570	0.9927	1.1298
1.5%	0.958	0.148	0.539	0.9978	0.9764
2.0%	2.474	0.335	0.470	0.9894	0.9149
2.5%	4.788	0.437	0.459	0.9952	0.9177
3.0%	7.182	0.421	0.481	0.9988	0.9952
3.5%	12.130	0.466	0.484	0.9884	1.1356
4.0%	15.641	0.544	0.478	0.9916	1.1242
4.5%	24.898	0.432	0.508	0.9962	0.9896
5.0%	34.234	0.406	0.533	0.9921	0.9541

Table 3.4. Rheological parameters calculated by H-B model (numerical method)

Bentonite percentage	**H-B (numerical method) parameters and *GoF***				
	τ_y (Pa)	k (Pa·s^n)	n	R^2	*BIV*
1.0%	0.414	0.071	0.573	0.9981	1.0083
1.5%	0.964	0.140	0.557	0.9994	1.0018
2.0%	2.267	0.324	0.490	0.9992	1.0012
2.5%	4.582	0.521	0.451	0.9998	1.0060

3.0%	7.418	0.564	0.451	0.9992	1.0059
3.5%	13.525	0.510	0.472	0.9963	1.0070
4.0%	17.249	0.424	0.515	0.9971	1.0249
4.5%	26.665	0.339	0.552	0.9988	1.0071
5.0%	36.523	0.272	0.604	0.9975	1.0345

The average values of the BP model's rheological parameters, together with the R^2 and *BIV* results, are summarized in Table 3.2. The average values of the H-B model parameters calculated using the API measurement method and API numerical method as well as the R^2 and *BIV*, and the results are summarized in Table 3.3 and Table 3.4, respectively. According to the data shown in Table 3.2, the highest values of R^2 and *BIV* that the BP model can provide are 0.77 and 0.69, respectively. Meanwhile, when the H-B model is adopted, for both API measurement and API numerical methods, no value of R^2 is lower than 0.9884, and the maximum deflection of *BIV* from 1 is only 0.1356, which is a significant improvement from the BP model. When we compare the two H-B methods, numerical method and the measurement method, numerical method not only show better *GoF* (higher value of R^2 and *BIV* closer to 1) but also presents fewer fluctuations for R^2 (Figure 3.7) and for *BIV* (Figure 3.8).

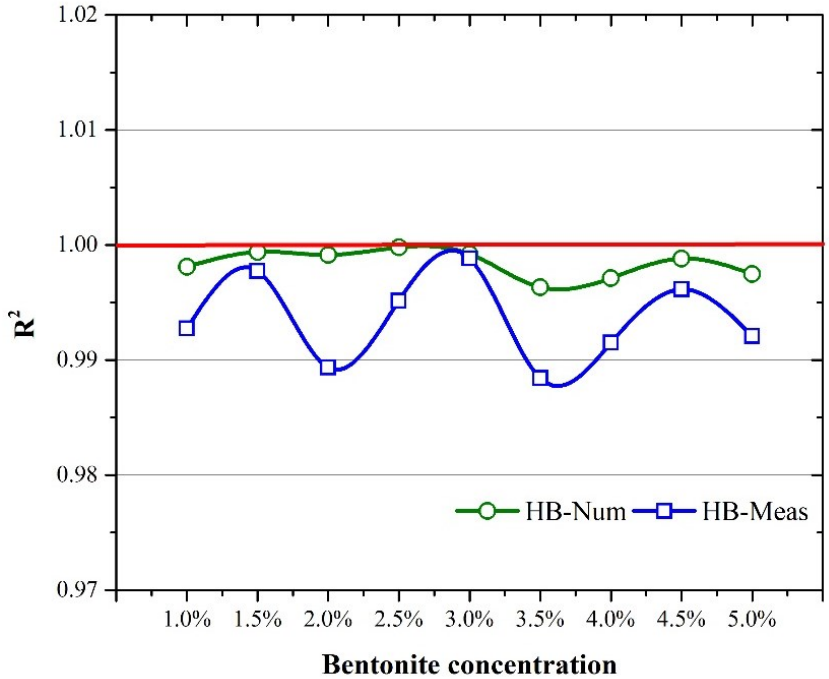


Figure 3.7 R^2 of H-B Models

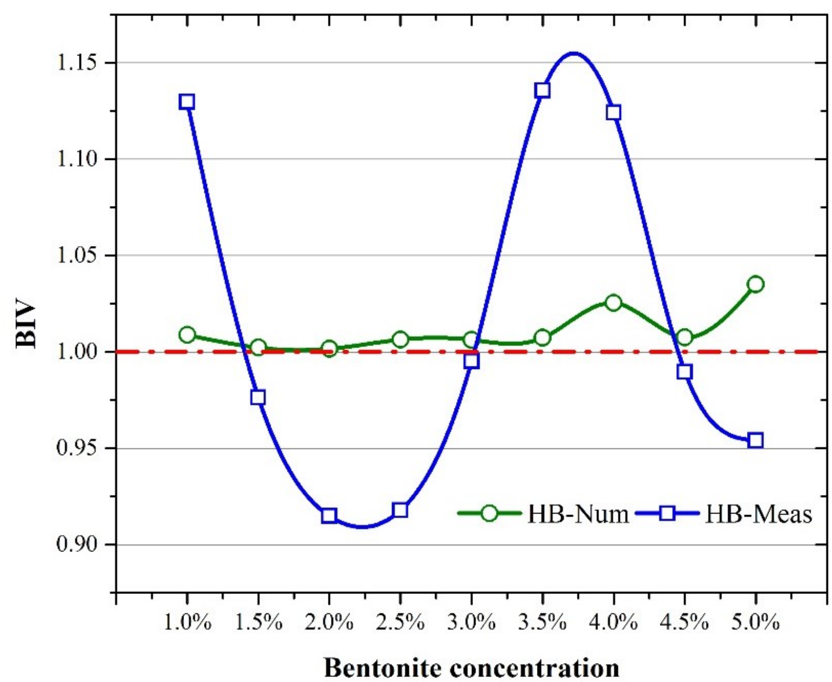


Figure 3.8 *BIV* of H-B models

3.4.3. Effects of Bentonite Concentration on Rheological Parameters

For each bentonite concentration, three tests were conducted, and the rheological properties of the three drilling fluids were determined. The average values of the rheological parameters, as well as their standard deviation (SD) based on the BP model and the H-B numerical techniques, are presented in Figure 3.9 and Figure 3.10, respectively. Figure 3.9 indicates that both *PV* and *YP* increase as the bentonite concentration increases. According to the values of error bars in Figure 3.10, the variations of *PV* and *YP* for all tests are small, and the maximum variation appears at 4% for both *PV* and *YP*, which are still acceptable considering the precision of testing devices (minimum precision is 1 lbf/100ft^2 or 0.4788 Pa).

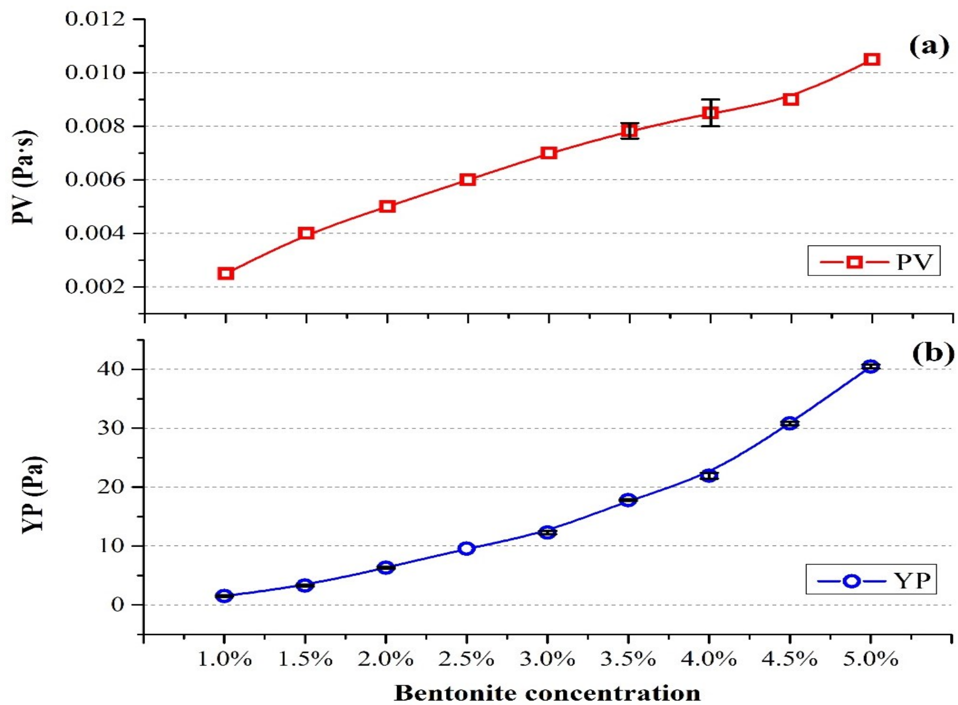


Figure 3.9 BP model parameters (a) Plastic Viscosity (b) Yield Point

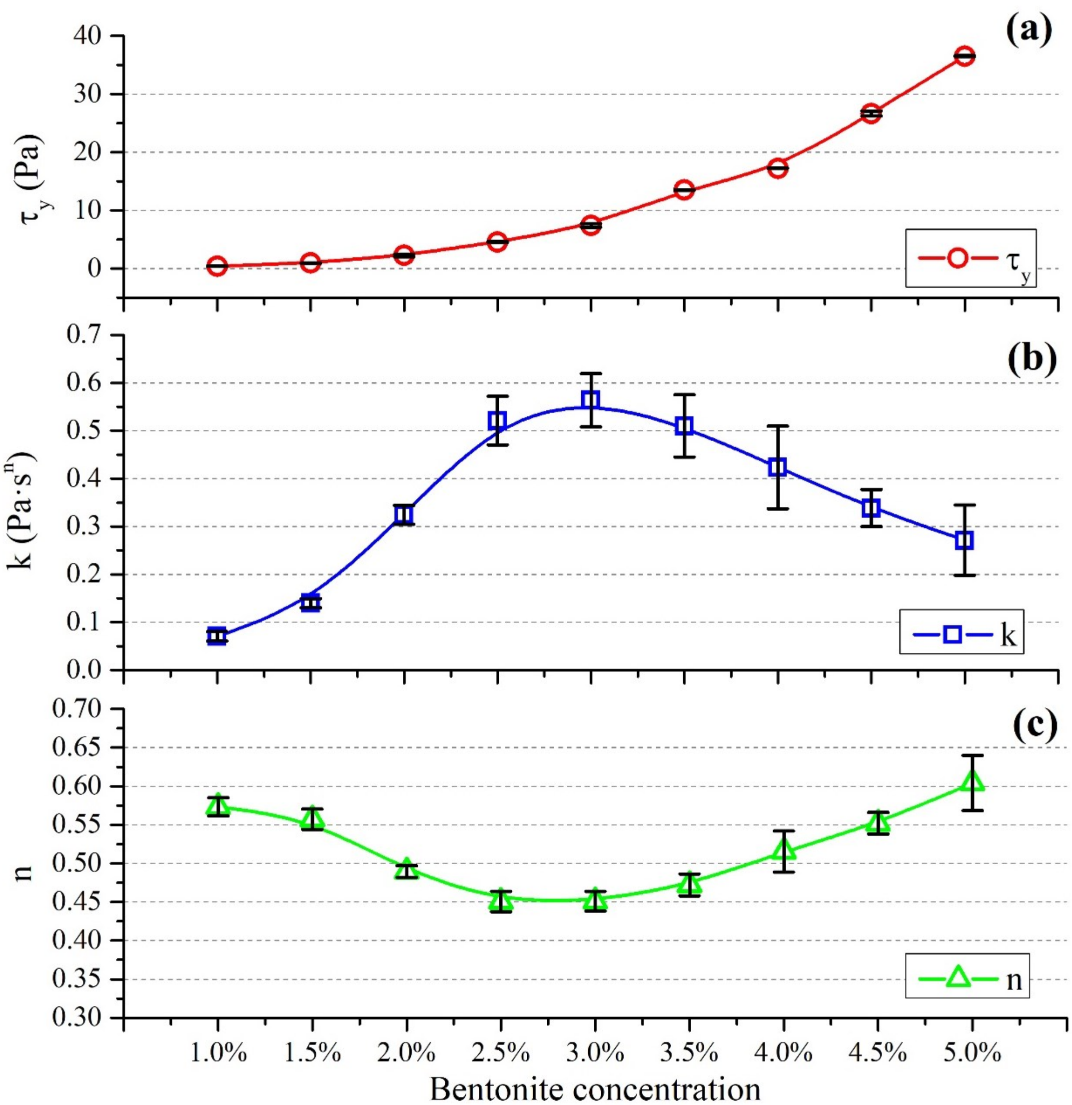


Figure 3.10 Herschel-Bulkley parameters (a) yield stress (τ_y) (b) consistency index (k) (c) flow behavior index (n)

In the H-B model, τ_y shows a similar increasing trend as *YP* with overall lower values, which again indicates the overestimation feature of the BP model. The maximum SD of τ_y is only 0.4278 Pa at 4.5% concentration. Meanwhile, k and n present complete opposite trends when adding more bentonite; k increases from 0.07 to the peak value of about 0.56 at 3%, and then drops to approximately 0.26 at 5%, while n decreases first from about 0.58

at 1% to 0.45 at 3%, and then recovers to around 0.6 at 5%. Compared to τ_y, k and n show much narrower range of variation but more significant SD. The procedure of obtaining τ_y, k, and n with non-linear regression by changing the estimated value of n minimizes the error. Thus, these three H-B parameters are all dependent on each other. However, it seems that τ_y relates more closely to the bentonite concentration, while k and n show more coordination to make the predicted curve better fit the measured data.

3.4.4. Hydraulic Behavior

Since the accuracy of the rheological parameters will affect the accuracy of the hydraulic behavior prediction, the H-B model with API numerical method is selected to be used in the further hydraulic parameter calculations due to its better *GoF*.

The obtained H-B parameters, τ_y, k, and n, were then introduced into the numerical program to calculate the hydraulic parameters, ΔP, τ_w, and h. The other relevant data remained constant: pipe outer diameter:14 cm (5.5 in); borehole diameter: 31 cm (12.25 in); and the drilling fluid flow rate: 1,461 L/min (386 gal/min). Calculated Reynolds numbers confirmed that all the flows are in laminar regime; therefore, the rheological properties will play an important role in the hole cleaning process (Zeidler 1972; Okrajni and Azar 1986; Becker et al. 1991).

Figure 3.11a to Figure 3.11d illustrate, how the hole cleaning performance indicators, *YP*/*PV* (Figure 3.11a) and h (Figure 3.11b), as well as the hydraulic parameters τw (Figure 3.11c) and ΔP (Figure 3.11d), vary as a function of the bentonite concentration. Note that the normalized plug width (*h*) is defined as the percentage of the annular gap occupied by the width of the plug zone of the velocity profile in the annulus

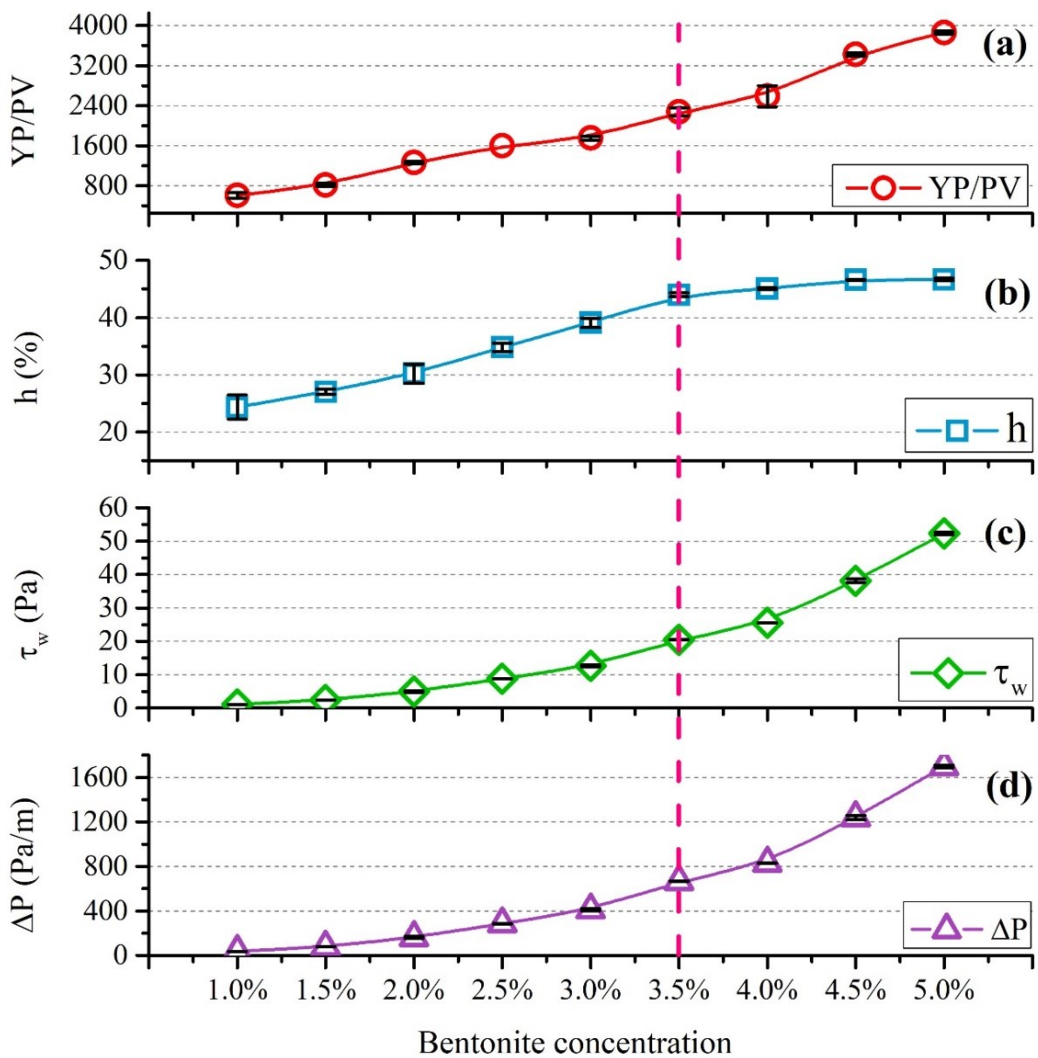


Figure 3.11 (a) *YP*/*PV* vs. Bentonite concentration (b) Normalized plug width (h) vs. Bentonite concentration Normalized (c) Wall shear stress (τ_w) vs. Bentonite concentration (d) Frictional pressure loss (ΔP) vs. Bentonite concentration

Figure 3.11a indicates that the *YP*/*PV* is a monotonic increasing function of the bentonite concentration. These findings are in line with the earlier results showing that *YP*'s rate of growth is greater than *PV*'s (Figure 3.9). The normalized plug width, *h*, also increases continuously with the increasing bentonite concentration (Figure 3.11b), however, the rate of growth of h is much less than the wall shear stress and the frictional pressure loss. When the concentration increases beyond 3.5%, adding more bentonite has little improvement in the growth of *h*.

The wall shear stress increases with the increasing bentonite concentration (Figure 3.11

Figure 3.11c). Frictional pressure loss, ΔP, also increases continuously with the increasing bentonite concentration (Figure 3.11d). This is expected as the τ_w is directly proportional to the frictional pressure loss. The frictional pressure loss and the wall shear stress are positively correlated with τ_y, k, and n. The yield stress, τ_y, increases dramatically, while k and n vary in opposing directions over a narrow range, which means that the τ_y has a predominant effect on the ΔP and the τ_w.

3.5. Discussions

In terms of rheological models, although the BP model is simple to use and can provide an accurate prediction at high shear rates (above 300 rpm or 510.9 s^{-1}), however, it will overestimate the shear stress at low shear rates, as well as give a yield point much higher than the yield stress. The low values of *GoF* also indicate that the BP model shows poor performance for the prediction of the drilling fluid rheological behavior. In particular, for HDD projects, the shear rates of the annular fluid flow are at a relatively low level, and the absence of the information about the low shear rate performance will hinder the accuracy of the predictions and further analyses. Meanwhile, the H-B model has three parameters, which include both the yield stress and the shear-thinning properties of the drilling fluid, and gives a better prediction of rheological behavior at all shear rates. Therefore, H-B model can be used for more accurate prediction of hydraulic behavior and the hole cleaning performance evaluation. The API numerical method is more complicated but can provide more accurate and stable predictions, which later benefits the more accurate prediction of the hydraulic parameters.

For rheological parameters, the dramatic increase of *YP* or τ_y both revealed that increasing bentonite concentration effectively enhances the structural strength of the drilling fluid, which is good for suspending cuttings when the pump stops. However, caution should be taken that excessively high yields may also induce high frictional pressure loss, which may induce borehole instability (due to higher dynamic bottomhole pressure) and cause more energy consumption (i.e. pump horsepower).

For drilling fluid suspension capacity, as the concentration of bentonite increases, τ_y and h both are increased. Although the h hits a plateau at high concentration, the high value of τ_y still can indict a remarkable improvement on suspension capacity by adding bentonite. In terms of sweeping capacity, although the ΔP and the τ_w showed a dramatical increase when more bentonite was added, it does not mean that the sweeping capacity of the drilling fluid was also enhanced. This is because of the reasons mentioned previously that higher concentration of viscoelastic fluids will also cause a higher additional normal force on the cuttings which need higher drag force (velocity) to be moved. In this case, at the same flow rate, a high concentration of bentonite will not only provide no or negative contribution to bed erosion but also raise the concern about borehole stability due to high annular pressure.

If the annular flow velocity is far below the critical value that can initiate the bed erosion, for example in the reaming process the flow velocity can reach as low as 0.01-0.02 m/s

(Yan et al. 2013), the drawbacks on bed erosion due to high concentration of bentonite may not be our major concern because the bed erosion cannot be initiated no matter what fluids we are using. A similar situation was also reported by Zeng et al. (2018) that changing drilling fluid property under low flow velocity (0.01 to 0.1 m/s) did not show any observable disturbance on the cuttings bed. In this case, the cuttings bed erosion will largely depend on the rotation of the drilling pipe in drilling (reaming) process or disturbance from the drill bit during the wiper trip. The primary function of drilling fluid is to suspend the cuttings after they are brought up from the bed by the drill pipe or the drill bit and transported them to the surface as soon as possible. This requires the drilling fluid to have good suspension capacity (high value of τ_y and h) to support the cuttings and good shear-thinning property (induce lower frictional pressure loss) to allow higher transport velocity.

If the annular flow velocity is in the medium range that can initiate the bed erosion, for example in small diameter pilot hole, lower viscosity (lower concentration of bentonite for this study) will improve the sweeping capacity. However, a lower concentration of bentonite also implies lower suspension capacity. Since it is almost impossible to cleaning the hole purely depends on fluid flow in the laminar region (the flow regime in most HDD annulus), the hole cleaning should always be assisted by drill pipe rotation or wiper trip, which means the suspension capacity is also important (Leising and Walton 2002). Therefore, to find the right bentonite concentration or formulation of drilling fluids (different combination of additives) to obtain a drilling fluid with sufficient suspension capacity while inducing relatively low frictional pressure loss is the key to solve this problem.

If the fluid is allowed to be pumped at extremely high velocity, even at turbulent regime, low viscosity fluids, like water, is widely observed to be better for hole cleaning due to the high drag force provided by turbulence (Duan et al. 2008; Ford et al. 1990; Leising and Walton 2002; Peden et al. 1990; Sifferman and Becker 1992). However, this situation is almost impossible in HDD annulus because of the limitation on pump capacity, allowable annular pressure or large diameter of borehole.

Finally, the conventional hole cleaning capacity indicator *YP/PV* will be discussed. Since *YP*/*PV* was used to indicate hole cleaning capacity by representing the flatness of the velocity profile of the fluid in the annulus, we plotted *YP/PV* and the plug width h in one graph for each bentonite concentration (Figure 3.12). We can easily find that as long as bentonite concentration stays below 3.5%, *YP*/*PV* and h have an approximately linear relationship (represented by the dashed line), which means that *YP/PV* can represent the relative flatness of the velocity profile for the drilling fluids under 3.5% bentonite concentration. However, when concentration goes higher (more than 3.5%) the curve starts to deflect from the dashed line and finally goes almost parallel to *YP*/*PV* axis, which indicates that the increase of bentonite concentration has a continuous effect on the growth of *YP*/*PV* but cannot increase h anymore. Since we found that the suspension capacity is improved with the increase of bentonite concentration due to the increase of τ_y, the higher value of *YP/PV* may still indicate better hole cleaning capacity due to higher suspension capacity but it does not guarantee a flatter velocity profile. Moreover, the YP/PV can not show the frictional pressure loss as well as the sweeping capacity we discussed above.

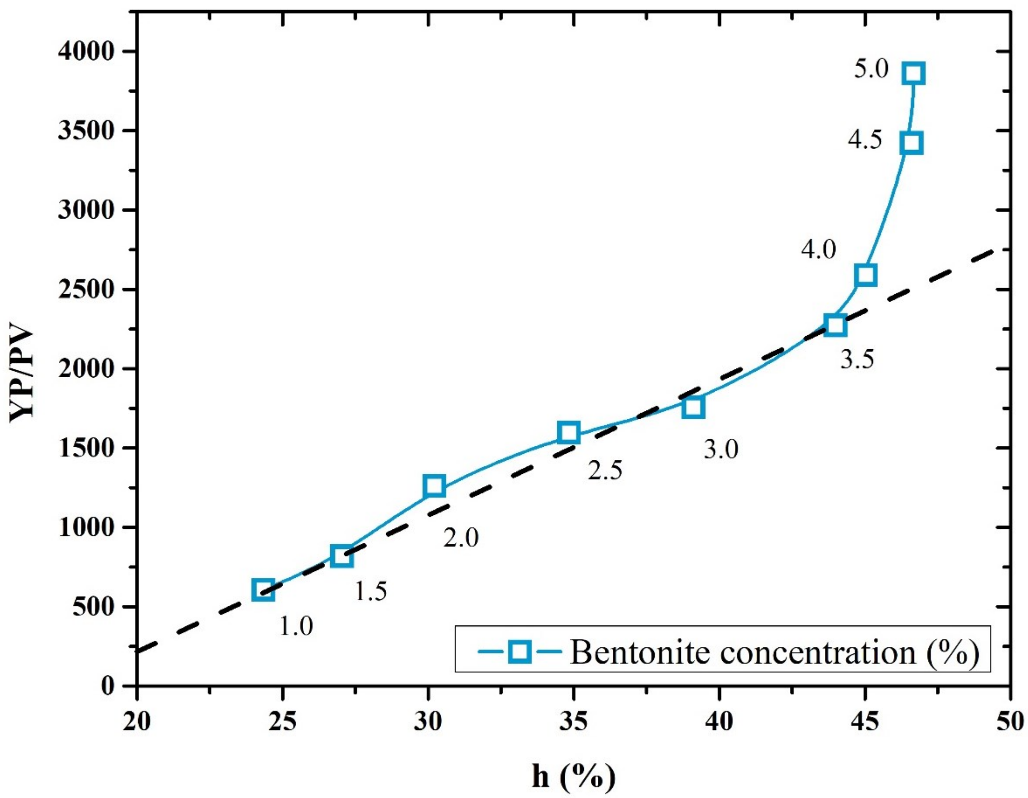


Figure 3.12 The correlation between parameters *YP*/*PV* and *h*

If *YP*/*PV* is the only index used as hole cleaning performance indicator, it may be concluded that adding more bentonite will provide better hole cleaning performance. However, when the new evaluation system is applied we can see that, although more bentonite will bring better suspension capacity, it also comes with high frictional pressure loss due to the increase of rheological parameters, which will impair the sweeping capacity of drilling fluid, raise borehole stability concerns and limit the allowable pump rate.

3.6. Conclusions

By conducting a series of viscometer tests, we have examined the accuracy of different rheological models and calculation methods for predicting rheological characteristics of clay-based drilling fluids as well as their associated hole cleaning performance. The results showed that the H-B model can provide more accurate predictions of rheological behavior compared to the conventional BP model. By comparing the two API recommended calculation methods for the H-B model, it was found the API numerical method can provide more accurate and stable goodness of fit (*GoF*), which is important for further hydraulic behavior predictions.

To indicate the hole cleaning capacity of drilling fluid, using the single indicator *YP*/*PV* will lead to the conclusion that the use of more bentonite (within the tested concentration range from 1% to 5%) in the drilling fluid is better for hole cleaning. However, based on the analyses combining rheological parameter with hydraulic parameters (calculated from the H-B model), the hole cleaning capacity of drilling fluid were divided into suspension capacity indicated by yield stress (τ_y) and plug width (h) and sweeping capacity which is higher with lower viscosity and can be indicated by lower frictional pressure loss under a given flow velocity. By adding bentonite, the suspension capacity of drilling fluid will be improved due to increasing of yield stress (τ_y) and plug width (h) even if the h hits a plateau at high concentration. On the other hand, although the increase of bentonite concentration leads to an increase on wall shear stress (τ_w) and frictional pressure loss (ΔP), it may not enhance the sweeping capacity of the drilling fluid. This is because an additional compressive force will exist in viscoelastic fluids, which will increase the resistive force against bed erosion. Therefore, adding more bentonite may not be helpful to erode the bed while induce high frictional pressure loss to either raise the risk of hydrofracture or limit the allowable flow velocity of drilling fluid.

The select of bentonite concentration or drilling fluid rheological properties should always rely on the real situation. Under the situation where the velocity is too low to even initiate the bed erosion, the sweep capacity of drilling fluid becomes negligible while the suspension capacity turns to be more important. In this case, the bed erosion should rely on the mechanical operation like drill pipe rotation or wiper trip. However, when the velocity becomes higher but not high enough to generate turbulence to fully clean the annulus, both suspension, and sweeping capacity matters. More theoretical and experimental works need to be down to finding the balance point between these two capacities.

For future study, physical simulation experiments should be conducted to verify suspension and sweeping capacity of drilling fluids under different flow and operation conditions. . Also, different additives should be applied to modify drilling fluid properties and to investigate their effects on drilling fluid hole cleaning capacity. Once the impact of drilling fluid rheological properties on the hole cleaning performance is properly evaluated, the process of choosing drilling fluid and additives could be optimized and the risks associated with hole cleaning problems will be minimized.

Chapter 4: Effects of Biopolymer Additive on Hole Cleaning Capacity of Water-Based Drilling Fluids in Horizontal Directional Drilling

4.1. Introduction

Horizontal directional drilling (HDD), as a fast-growing trenchless construction method, is an outgrowth of the directional drilling from oil and gas well drilling industry (Willoughby 2005). Using HDD, pipelines can be installed beneath rivers or existing buildings and utilities with minimal surface excavation (Ariaratnam et al. 2007; Sarireh et al. 2012). Compared to the conventional open-cut method, HDD is generally more cost effective due to its less environmental and social impact, especially in a congested urban area (Lueke and Ariaratnam 2005; Woodroffe and Ariaratnam 2008). However, since HDD shares lots of common features with oil and gas well directional drilling, they both encounter similar problems. One of the major concerns is the cuttings transport in horizontal or high inclined wells, also known as hole cleaning problem.

During the HDD process, the cuttings are generated as the drill bit penetrates into the ground and are supposed to be transported out to the surface by the drilling fluid. Inefficient cuttings transport will make the cuttings settle at the low side of the annulus and form the cuttings bed (Jawad 2002). As the thickness of the cuttings bed increases, the volume of the annular space is diminished which will lead to a series of problems, such as rising of annular pressure, increasing of torque and drag force and even causing stuck pipe (Pilehvari et al. 1999).

The mechanisms of cuttings transport in vertical wells which has been studied in the petroleum industry are significantly different from that in horizontal wells. The major difference is that the cuttings travel distance in horizontal wells is usually in inches which is much shorter than tens or hundreds of feet in vertical wells (Caenn and Chillingar 1996). It has been proven that the turbulent flow is more effective than laminar flow on cuttings transport in horizontal wells (Mohammadsalehi and Malekzadeh 2011; Okrajni and Azar 1986) However, the features of HDD, like low pump capacity, large annular space and limited allowable annular pressure due to shallow buried depth, all restricted the flow in laminar region. Thus, it becomes more important to investigate the relationship between drilling fluid properties and its hole cleaning capacity for HDD applications.

Water-based drilling fluid is the most commonly used material in the HDD process, which is formulated with water and additives (Ariaratnam and Beljan 2005; Caenn and Chillingar 1996). Bentonite is the most commonly used additive or base material since it can highly be dispersed in water after hydration which gives multiple functions to the drilling fluids: (1) the yield stress and gel strength provides suspension to cuttings when pump stops, (2) density of the fluid produces hydrostatic pressure to balance the ground pressure to provide stability to the borehole, (3) filter cake can form on the borehole wall to reduce fluid loss to the ground (Ariaratnam and Beljan 2005). To modify the drilling fluid properties, polymers are another frequently used additive. The polymers used in drilling fluids are usually organic chemicals with high molecular weight (above 200) (Caenn and Chillingar 1996). They can be categorized into three kinds: natural, modified natural and synthetic, which provide different functions to the drilling fluids, like modifying rheology, reducing filtration loss, enhancing lubrication, prohibiting clay swelling etc. Among these additives, biopolymers which are polysaccharides manufactured from bacterial fermentation, are found to be good at modifying low-shear-rate properties of drilling fluid which enhancing their cuttings suspension and carrying capacity (Beck et al. 1993; Caenn and Chillingar 1996; Powell et al. 1991).

4.2. Background

4.2.1. Rheological Models

Rheological model is an approach to describe the relationship between shear stress and shear rate for fluids and can also be used to calculate the drilling fluid hydraulic parameters in the annulus, such as the pressure loss, viscosity and velocity profiles (Ariaratnam et al. 2007; Kelessidis et al. 2006). Several rheological models have been used for describing the rheological behavior of drilling fluids in the past such as Bingham plastic model, power law model, Herschel–Bulkley model (also known as yield power law model) and Robertson-Stiff model (Robertson and Stiff 1976). However, the Bingham plastic model, power law model, the Herschel–Bulkley model are the three most commonly used ones in HDD application.

4.2.1.1. Bingham Plastic Model

The Bingham plastic (BP) model has two parameters to describes the relationship between shear rate (γ, s^{-1}) and shear stress (τ, Pa). The equation can be expressed as:

$$\tau = YP + PV\gamma \tag{4-1}$$

where YP is the yield point (Pa) and PV is the plastic viscosity (Pa·s). The YP is the minimum shear stress corresponding to the first evidence of flow for Bingham plastic fluids (Dzuy and Boger 1983) and the PV is equal to the slope of the linear shear stress-shear rate relationship above the yield point. They are obtained by plotting the shear stress measurements at 300 rpm (510.9 s^{-1}) and 600 rpm (1021.8 s^{-1}) in viscometer tests (Ariaratnam et al. 2007). Most drilling fluids are pseudoplastic which exhibit a decrease in "viscosity" with the increase of shear rate. Therefore, using only the data measured at a high shear rate will result in a poor prediction of fluid behavior at low shear rates. In addition, the shear rate that drilling fluids experience in the annulus is usually at the lower range. Chin (2001) gave a numerical modeling result that in most case the annular shear rate is lower than 20 s^{-1}. Since most of the previous research about effects of rheological properties on hole cleaning capacity is based on Bingham plastic model, extra caution should be taken when adopting their conclusions or rule of thumb in practical application, the details will be discussed in the next section.

4.2.1.2. Power law Model

The power law (PL) model can better describe the pseudoplastic properties of drilling fluids than Bingham plastic model by using two parameters, the consistency index k ($Pa \cdot s^n$) which indicates fluid resistance to flow, and the flow behavior index n that shows the degree of pseudoplastic or shear-thinning behavior of the fluid. The shear stress-shear rate relationship is defined by the Eq **Error! Reference source not found.**:

$$\tau = k \cdot \gamma^n \qquad (4\text{-}2)$$

The problem with the power law model is that it does not account the yield stress of the drilling fluid, which not only gives poor prediction at low shear rate range but also provide lack of insufficient information required for drilling fluid hole cleaning capacity analysis.

4.2.1.3. Herschel-Bulkley Model

The Herschel-Bulkley (HB) model, also known as yield-power law model, has three parameters: the yield stress τ_y (Pa), the consistency index *k* (Pa·s^n) and the flow behavior index n. The τ_y is similar to *YP* in Bingham plastic model but is obtained by using the regression analysis of the shear stress data measured at multiple shear rates ranging from (1021.8 s^{-1}) to low shear rate (5.109 s^{-1}). The other two parameters *k* and *n* are similar to that in the PL model, but the values are different due to the consideration of τ_y (Hemphill et al. 1993). The HB model is defined by the Eq. (4-3):

$$\tau = \tau_y + k\,\gamma^n \qquad (4\text{-}3)$$

It has been widely proven that for drilling fluids exhibiting yield stress and pseudoplastic properties, the HB model can provide a more accurate prediction on both rheological parameters and hydraulic behaviors (Hemphill et al. 1993; Hussain and Sharif 1998; Kelessidis et al. 2006; Ofei 2016). Therefore, this study will mainly focus on using HB model to investigate the effects of drilling fluid rheological parameters on the cuttings transport.

4.2.2. Effects of Drilling Fluid Rheological Properties on Hole Cleaning

Since the early 80's, researchers have conducted numerous experimental studies to investigate the factors controlling the hole cleaning in deviated and horizontal wells. Among all the factors, drilling fluid velocity and rheological properties show the most effectiveness and controllability (Adari et al. 2000; Azar and Sanchez 1997; Nazari et al. 2010). It has been proven that as long as the velocity is high enough, the cuttings can be removed regardless of other conditions (Saintpere et al. 2000). The critical velocity in horizontal wells to provide sufficient hole cleaning is much higher than that in vertical wells. Li and Luft (2014) replotted Larsen's (1990) experimental data and found that the critical velocity required for hole cleaning in vertical and horizontal wells are about 0.69 m/s and 1.67 m/s respectively. However, the pump capacity and limited annular pressure capacity all restricted the available flow velocity in HDD annulus, especially in the back-reaming stage when the borehole is enlarged. The field data provide by Shu et al. (2015) showed that for a 1219 mm pipe installed in a 945m borehole, the annular flow rate varied from 0.7 m/s in the pilot borehole to about 0.02 m/s in the final reaming cycle. Zeng et al. (2018) also pointed out that the flow velocity was usually below 0.4 m/s for borehole diameter up to 800 mm. This makes hole cleaning operation only depending on the high fluid velocity become unrealistic in HDD (Leising and Walton 2002; Shu et al. 2015). Therefore, the investigation of the relationship between drilling fluids rheological properties and their hole cleaning capacity becomes more urgent in the HDD industry.

4.2.2.1. Researches in oil and gas industry

At the pioneering research stage dated back to the early 1940s', the rheological properties of the drilling fluid are usually described by the two parameters viscosity and the gel strength. Since the viscosity of non-Newtonian fluids will change with shear rate, the viscosity used in the literature usually refers to the apparent viscosity measured at a certain shear rate. There was a debate about whether the low viscosity or high viscosity is better for hole cleaning (Pigott 1941; Williams and Bruce 1951). Tomren et al. (1986) found that in the vertical annulus the low viscosity fluid in turbulent flow can clean the borehole as well as high viscosity fluid does in laminar flow while on the other hand the turbulent flow is preferred in high inclination wells. In the same year, Okrajni and Azar (1986) conducted a series of flow loop tests and found that in laminar flow, a higher value of yield point over plastic viscosity ratio (YP/PV) provided better cuttings transport for all inclination and was more significant for low annular velocity. They also found that the higher the YP/PV was, the lower the value of the power law flow behavior index n, and the flatter the velocity profile which is claimed to be good for hole cleaning. Although the authors did not give a detailed explanation, the benefits of a flatter velocity profile related to hole cleaning were confirmed by other researchers, which will be introduced in detail later.

Adari et al. (2000) conducted hole cleaning experiments in an 80 ft (24.4 m) flow loop at an inclination angle of 87 degrees. Different polymer drilling fluids were tested, and their rheological behavior was described using the power law model. They found that fluids with a higher value of n/k (power law parameters), which indicates low effective viscosity, provided better hole cleaning performance at the given pump rate. This is because low viscosity fluids are easier to be pumped in turbulent flow which is superior to the laminar flow for hole cleaning in highly inclined wells. Interestingly, they also found that high viscosity (low n/k) combined with high flow velocity gave the optimum conditions for hole cleaning and concluded that more efficient erosion of the bed was caused by the high wall shear stress. However, in HDD wells especially in sand and gravel layers, a certain degree of viscosity is required to reduce filtration loss and balance the formation pressure, moreover, pumping viscous fluids at extremely high velocity is not practical due to the reasons mentioned previously. Therefore, determining what rheological property is good for hole cleaning under the low flow velocity is of more importance for the HDD industry.

Powell et al. (1991) studied the properties of biopolymer drilling fluid as well as their hole cleaning capacity. They found that for Xanthan and Welan fluids which exhibited excellent viscoelastic (high true yield stress (TYS)) and shear-thinning properties not only provide good suspension to the cuttings at static state but also provide flatter velocity profiles. Unlike the pseudoplastic fluids with zero yield stress which are sheared (thinned) across the entire annulus, these biopolymer fluids flew with an unsheared plug region in the center and shear thinned layers confined to the wall (Figure 4.1). Due to the shear-thinning properties, the zero or low shear rate plug region possess high viscosity while the confined layers near the wall show lower viscosity under high shear rate. These features bring multiple advantages regarding hole cleaning:

(1) High shear rate and shear stress near the borehole wall enhance the cuttings bed erosion.

(2) Lower pump pressure is provided by high shear-thinning property, which allows higher pump rate.

(3) Distribution of the flow stream is improved by skewing more flow to the low side in horizontal and eccentric annuli which, to a certain extent, can offset the uneven distribution caused by eccentricity of the drill pipe.

(4) The high viscosity in the plug region provides good suspension to the cuttings, and the drag force in this region is distributed more evenly which reduces the rotation of the cuttings and its movement towards the wall (Al-Kayiem et al. 2010). Cuttings in this kind of flow profile tend to migrate towards the core region where high viscosity can provide better suspension (Powell et al. 1991).

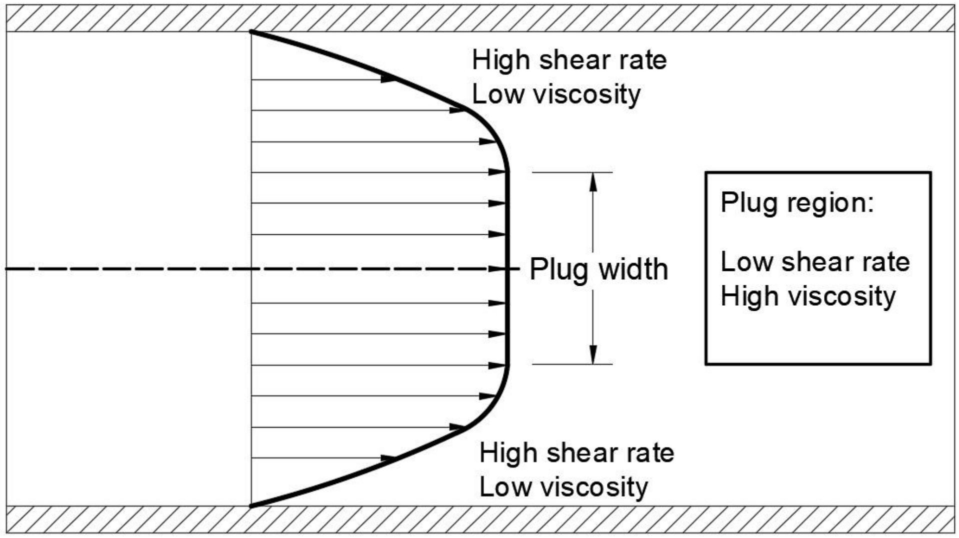


Figure 4.1 Flattened velocity profile in the annulus

A similar phenomenon was also observed by Zamora et al. (1993) that sand particles were evenly distributed and fully suspended across the "plug-like" velocity profile in a laboratory simulation. A point worth noting in their testes is that for the drilling fluid with 3 ppb (8.55%) biopolymer which had a lower value of YP/PV than the drilling fluid with 2 ppb (5.7%) biopolymer showed flatter velocity profile instead and provided better cleaning under the same flow rate. Both Powell et al. (1991) and Zamora et al. (1993) found that drilling fluids hole cleaning capacity in horizontal wells were more related to their low-shear-rate properties, like low-shear-rate viscosity (LSRV), TYS, storage modulus (G′) and loss modulus (G″), rather than parameters measured at high shear rate, like YP and PV from Bingham model. Moreover, better shear thinning property or lower n value will also promote the flattening of the velocity profile and reduce frictional pressure loss.

4.2.2.2. Researches in HDD industry

Zeng et al. (2018) recently conducted flow loop experiments focusing on simulating hole cleaning procedures in large diameter HDD annulus. They investigated the effect of flow velocity, drilling fluid rheological properties (based on the Bingham plastic model), hole angles and drill pipe rotation on the formation and broken of the cuttings bed. The flow rate was restricted to a very low level, from 0.01 m/s to 0.1 m/s. When there was no pipe rotation, they found that neither increasing flow rate nor changing rheological properties of drilling fluids did observable disturbance on the pre-existent cuttings bed. However, when drill rod was rotated, the physical contact between the rod and cuttings bed as well as the swirled flow could bring the cuttings to the mainstream and the cuttings would be transported for a certain distance depending on the drilling fluid velocity, rheological properties and cuttings properties. This important observation not only confirms previous conclusions that pipe rotation can significantly promote the hole cleaning performance in directional drilling (Denney 2008; Sanchez et al. 1997) but also implies that the drilling fluid's function in hole cleaning performance at low flow velocity, especially when the velocity is too low to initiate bed erosion, relies more on its suspension to the cuttings rather than erosion to the cuttings bed.

The objective of this study is to investigate the effects of additives on drilling fluid rheological properties and hydraulic behaviors in the HDD annulus and link them to the hole cleaning process to help evaluate the hole cleaning capacity of the drilling fluid. Commonly used biopolymer additive (Xanthan Gum) was used independently and together with bentonite, respectively, to formulate various water-based drilling fluids. Their effects on the potential hole cleaning capacity of drilling fluids were investigated. A new hole cleaning capacity evaluation method based on the Herschel-Bulkley model is proposed to help the optimum formulation of drilling fluid in the HDD field, and potential directions are proposed for future research.

4.3. Methodology

According to the above introductions, it can be found that both low viscosity fluid at turbulent flow and high viscosity fluid at laminar flow can provide good hole cleaning performance. This can be explained in two aspects:

First, the two components of the hole cleaning capacity of drilling fluid, suspension and sweeping, which were mentioned in Chapter 3. By comparing hole cleaning performance of polymer fluids with water, Walker and Li (2000) reported that polymer fluids (high viscosity) are more effective than water (low viscosity) in terms of carrying capacity but are weak at eroding a stationary bed.

Second, the drill pipe rotation. Drilling fluids with high suspension capacity usually have a high viscosity which results in their weak sweeping capacity. If the cuttings cannot be removed from the bed to enter the flow regime, they have no chance to be suspended and transported. Therefore, drill pipe rotation is indispensable when the drilling fluid with high suspension is pumped. The mechanical agitation of the drill pipe to the cuttings bed will significantly compensate the drilling fluid's weak erosion to the bed.

On the other hand, "viscosity" is only a commonly used term to give a general description of the drilling fluid property. The other parameters like LSRV, TYS, shear-thinning properties give a more detailed and precise description of drilling fluid rheological behavior. Since the suspension capacity is more related to the low-shear-rate properties like LSRV and TYS (Beck et al. 1993; Powell et al. 1991), which is only one part of the fluid apparent viscosity at flow state. If the shear-thinning properties can be improved, like decreasing the *n* value, a relatively lower apparent viscosity can be achieved and generate less frictional pressure loss caused by the drilling fluid viscous property. In this case, not only can the drilling fluid sweeping capacity be improved (less viscosity leads to less resistive forces) but also the annular pressure concern will be reduced and the higher flow rate is allowed.

4.3.1. Hole Cleaning Related Parameters

To achieve good hole cleaning capacity, rheological properties and hydraulic behavior that drilling fluids should provide in HDD can be summarized as:

4.3.1.1. Sufficient low-shear-rate properties.

These properties are all related to the interparticle association of the polymer molecules or clay particles in the fluids and can be presented by parameters like TYS, LSRV, G′ and G″. Beck et al. (1993) and Powell et al. (1991) showed that LSRV, G′ and G″ all correlate to TYS. In addition, TYS can be approximately obtained by using Fann 35A viscometer in the HDD field while the LSRV is measured by the rheometer which can measure the shear stress at really low shear rate level (0.06 s^{-1}) and G′ and G″ require oscillatory rheometers which not widely used in field applications. Therefore, yield stress (τ_y) obtained by using Fann viscometer associated with HB model is used as the suspension capacity index of the drilling fluid.

The structural feature indicated by the high value of τ_y can provide good suspension to cuttings when the pump stops and diminishes the potential for the build-up of cuttings bed. Besides, under flow condition, the higher value of yield can widen the unsheared plug region (plug width) which minimize the shear-thinning area of the mainstream across the annular space, and hence, reduce the settlement of cuttings in radial direction.

4.3.1.2. Frictional pressure loss

When flow rate and other conditions like annular dimensions, cuttings properties are constant, the frictional pressure loss is the function of drilling fluid rheological parameters (τ_y, k and n if H-B model is used). These three parameters are directly related to the apparent viscosity of the fluid as well as the frictional pressure loss. As mentioned above, sufficient τ_y is required to provide suspension to the cuttings, therefore, k and n should be kept as low as possible to provide relatively better sweeping (if the flow velocity is high enough to initiate bed erosion) and reduce the frictional pressure loss. Even if the flow velocity is too low to initiate bed erosion, the low frictional pressure loss can also reduce the annular pressure, lower the risk of hydrofracture or allow higher flow rate.

4.3.1.3. Flattened velocity profile.

The goodness of flattened velocity profile has been stated previously. Instead of using *YP*/*PV* or power law n value, the flatness of the velocity profile will be represented by the plug width (h_p, m) calculated based on HB model and slot annulus assumption. The annulus is approximated into a slot with a gap (H, m) equivalent to the difference between borehole radius and drill pipe radius (Figure 4.2). The equation of h_p, given by Kelessidis et al. (2006), can be expressed as:

$$h_p = \frac{2\tau_y}{\Delta P} \tag{4-4}$$

with the yield stress τ_y (Pa) and frictional pressure loss ΔP (Pa/m).

In order to compared situations in different annuli, the plug width hp is normalized as h (%) = h_p/H.

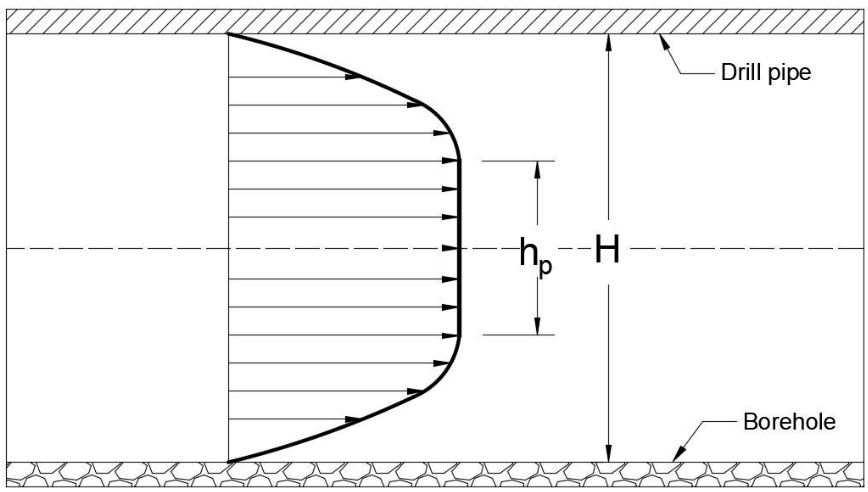


Figure 4.2 Plug flow in the annulus approximated as a slot

Based on fluid mechanics, the width of the plug region is directly proportional to TYS and inversely proportional to frictional pressure loss (Beck et al. 1993; Nguyen and Boger 1992). Therefore, h_p is also a function of HB parameters, τ_y, k and n, and shows a negative correlation with k and n. This implies that lower k and n values are not only good for reducing frictional pressure loss but also help to flatten the velocity profile, which allows more area of the annular space to be occupied by this high viscosity region to provide better suspension.

4.3.2. Evaluation Method

As discussed previously, the drill pipe rotation can apply disturbance and erosion on the cuttings bed, which can be provided by most HDD rigs. The maximum rotary speed can vary from 100 rpm to 260 rpm depending on the size of the rig (Ariaratnam et al. 2007). The bed erosion caused by the mechanical agitation of drill pipe rotation can significantly compensate the weakened sweeping capacity of the drilling fluid due to low velocity in the HDD annulus. Generally, the drilling fluid with good hole cleaning capacity should have sufficient TYS to provide suspension to the cuttings under both static and dynamic conditions. Meanwhile, the frictional pressure loss caused by fluid viscous property (*k* and *n*) should be kept as low as possible to increase sweeping capacity, reduce hydrofracture risk and to enable a larger flow rate. These two features work together to provide a flatter velocity profile.

After obtaining viscometer readings of each drilling fluid sample, the BP parameters *YP* and *PV* as well as the HB parameters τ_y, k, and n were calculated using methods described by API RP 13D (2010). The non-linear regression method, known as API numerical techniques, was used for HB parameter calculation.

Then the method for frictional pressure loss calculation was also adopted from API RP 13D (2010). Besides the obtained HB parameters, τ_y, k, and n, the other geometric and operational parameters were set to be constant: borehole diameter is 31 cm (12.25 in), drill pipe outer diameter is14 cm (5.5 in) and the drilling fluid flow rate is 1,461 L/min (386 gal/min) which results in an annular velocity of 0.4 m/s (1.32 ft/s). The wall shear stress and shear rate as well as critical Reynolds number where the flow regime changes from laminar to transitional flow were also determined using the procedure outlined in API RP

13D (2010). Finally, the plug width of each fluid was obtained by substituting τ_y and ΔP into Eq. 4. A spreadsheet was used for the calculation.

The trend of the plug width for drilling fluids with various components will be compared with their YP/PV values to verify whether the higher value of YP/PV is a reliable index for flatter velocity profile. In the new evaluation system, the rheological and hydraulic parameters will be discussed together to reveal how the additives impact the hole cleaning capacity of the drilling fluids.

4.3.3. Materials and Experiments

4.3.3.1. Materials

A commercial product, EXTRA HIGH YIELD™ bentonite, which is widely used in mineral exploration, water wells, and directional drilling operations was used for the preparation of base fluid. The cation exchange capacity (CEC) of this bentonite is 209.8 meq/100g, which is much higher than the normal range (70-130 meq/100g) given by Caenn et al. (2011). The impact of this high CEC will be discussed later. Xanthan Gum (XG) was selected as the biopolymer additive, which is a natural high molecular weight polysaccharide manufactured from bacterial fermentation (Caenn and Chillingar 1996).

4.3.3.2. Experimental procedure and apparatus

The Hamilton Beach™ HMD400 120V Triple Spindle Mixer was used for sample preparation, and the Fann 35A Viscometer was used for rheological property tests (Figure 4.3).

(a) (b)

Figure 4.3 (a) Hamilton Beach™ HMD400 120V Triple Spindle Mixer (b) Fann 35A Viscometer

Four groups of samples were prepared with different bentonite concentration varying from 0% to 3% with an increment of 1%. For each group, six samples were prepared with different biopolymer concentrations, ranging from 0% to 0.5% with an increment of 0.1%, except for group one (0% bentonite) in which the concentration range of additives was from 0.1% to 0.5%. Based on the main components of the samples, they were labeled as #0-1, #0-2 … #3-5, in which the first number indicates the bentonite concentration ("1" stands for 1%) while the second represents the biopolymer concentration ("1" stands for 0.1%). As for the sample preparation, bentonite and/or additive was added to 350 ml distilled water and mixed for 20 min. Then, the fluids were sealed and left in room temperature (20 °C) for aging about 4 hours. Before conducting the viscosity measurement tests, each sample was stirred for 2 min under 18000 rpm. Although the recommended stirring time is 5 min (API RP 13I 2009), it was found that long-term stirring would raise the temperature of the drilling fluid significantly which will change the rheological properties. Therefore, the time was controlled under 2 min to keep the temperature at 20 °C.

The viscometer tests also followed the instruction of API RP 13I (2009) using Fann 35A viscometer. Dial readings were recorded for rotary speed from 600 to 3 rpm, corresponding to shear stress under the shear rate from 1021.8 s^{-1} to 5.109 s^{-1}.

4.4. Results and Discussions

4.4.1. Results

4.4.1.1. Effects on Rheological Properties

According to the measured viscometer data, rheological parameters were calculated based on both BP model (*YP* and *PV* as well as *YP*/*PV*) and H-B model (τ_y, k, and n), the specific values are shown in Appendix (Table A-1). The estimated shear stress-shear rate relationship based on HB model are plotted together with the measured data on the same graph for each group (Figure 4.4 to Figure 4.7).

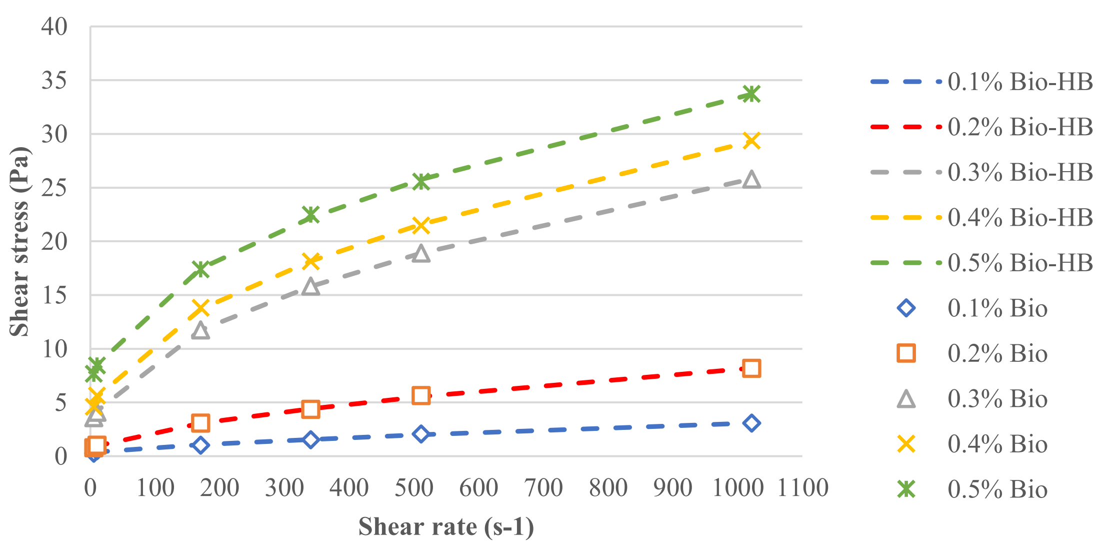


Figure 4.4 Rheograms of 0% bentonite with the biopolymer and estimated rheograms of HB model

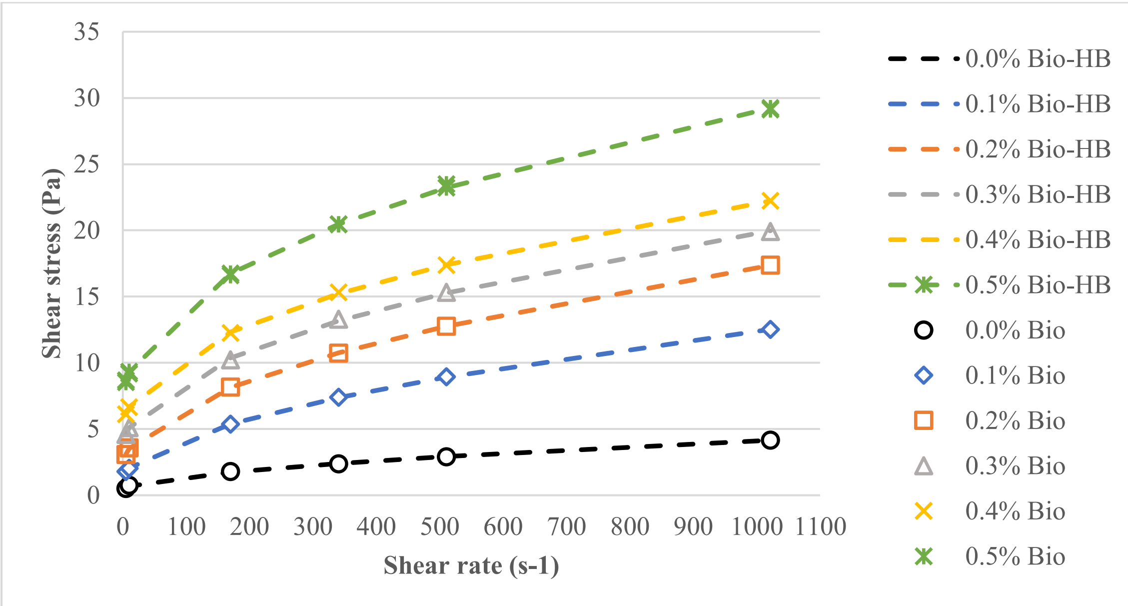


Figure 4.5 Rheograms of 1% bentonite with the biopolymer and estimated rheograms of HB model

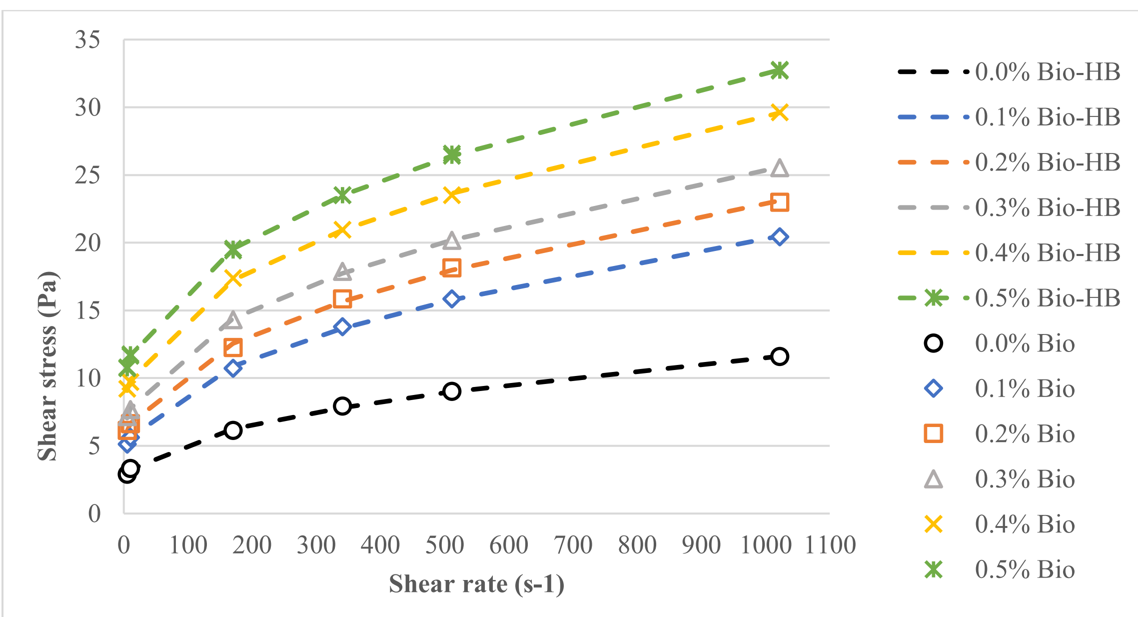


Figure 4.6 Rheograms of 2% bentonite with the biopolymer and estimated rheograms of HB model

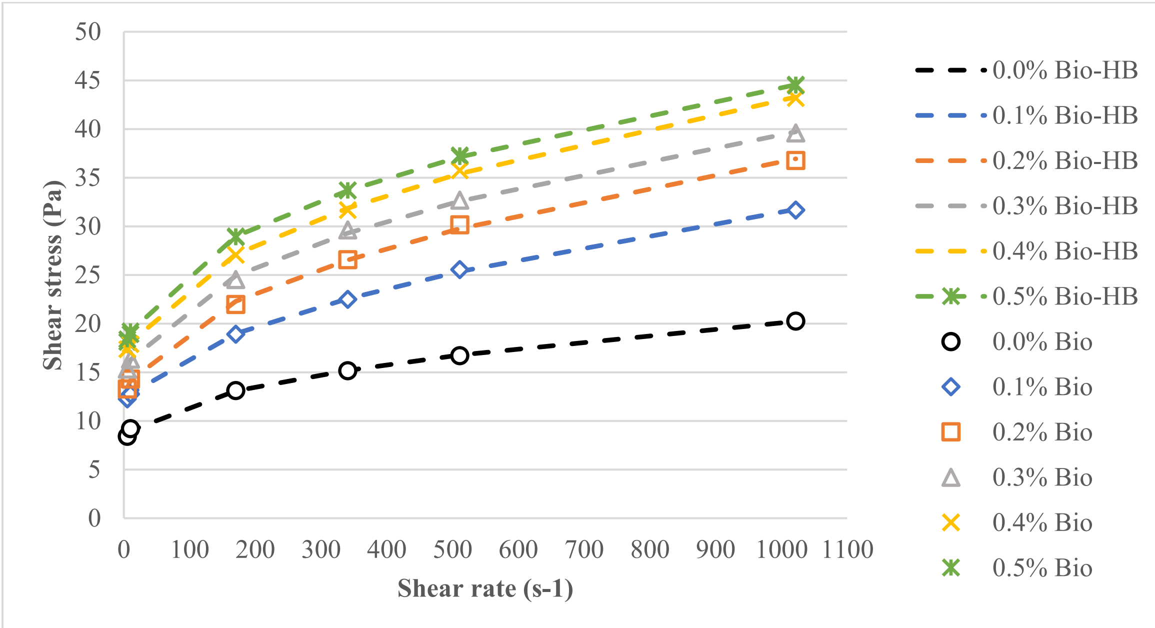


Figure 4.7 Rheograms of 3% bentonite with the biopolymer and estimated rheograms of HB model

From Figure 4.4 we can find that the trend of rheograms change dramatically when biopolymer concentration increases from 0.2% to 0.3%. At low concentration (0.1% and 0.2%), the low shear rate readings are close to zero, and the slopes of the curve are also flatter than higher concentrations. This maybe explained by the critical polymer concentration (CPC) concept proposed by Powell et al. (1991). The CPC was defined as the minimum effective polymer concentration for suspending and transport solids under a given condition. Above a certain CPC, the intermolecular association will be raised dramatically and form complex structured networks which will result in a significant change in the rheological behavior of the fluid. Since the CPC is correlated with various fluid and well conditions, we cannot conclude that 2% is the CPC in our case. However, the sudden change of the rheograms implies that we must have hit a certain CPC that is related to more intensive intermolecular association caused by the increased polymer concentration.

For group 2 to group 4 (Figure 4.5 to Figure 4.7), the observable change of characteristics of the rheograms only occurs when drilling fluids change from pure bentonite based to the bentonite-polymer mixture (from 0% to 0.1% biopolymer). Meanwhile, the increase of biopolymer concentration will raise the low-shear-rate stress and effective viscosity at any given shear rate. This can be explained by the adsorption of the polymers on the clay surface which enhance the interaction between clay particles (Theng 2012).

To better understand the effect of bentonite concentration as well as additive concentration to the rheological properties of drilling fluid, the HB parameters τ_y, k and n for each group are plotted (Figure 4.8 to Figure 4.10). Figure 4.8 shows that τ_y for each group sees a significant growth as more biopolymers added. For pure bentonite drilling fluids, more bentonite concentration will also provide a decent increase in yield stress. If we take the pure bentonite samples as the references, by adding up to 0.5% of biopolymers the increments of τ_y are 5.3 Pa, 5.9 Pa, 6.2 Pa and 7.3 Pa for group 1 to 4 respectively. This implies that bentonite can also enhance the function of biopolymers on the improvement of τ_y. As mentioned before, the higher the τ_y, the better the suspension and carrying capacity the drilling fluids can provide, however, Kenny et al. (1994) suggested 3 Pa as a lower limit of τ_y for fluids to provide functional suspension. Although this value can vary depending on other conditions like flow rate, cuttings properties, and borehole geometries, it still implies that it may be less meaningful to discuss the suspension capacity of the drilling fluids with low yield stress.

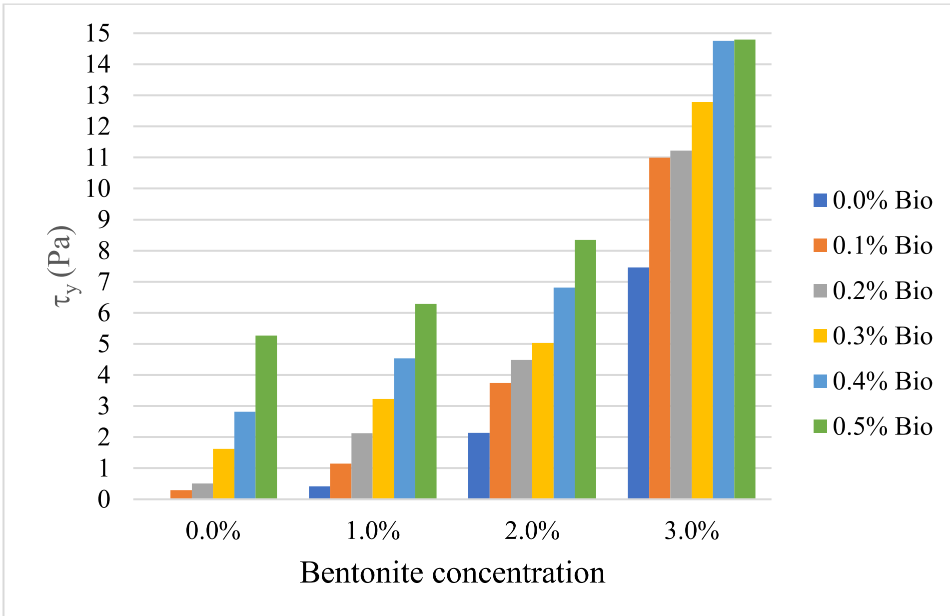


Figure 4.8 Herschel-Bulkley yield stress (τ_y) of drilling fluids

Although *k* and *n* are also important parameters which represent the drilling fluid properties under dynamic conditions, comparing *k* or *n* independently is not appropriate. Unlike yield stress which is a structural parameter related to fluid material property which can be measured directly (Kelessidis and Maglione 2008; Nguyen and Boger 1992), the values of *k* and *n* is obtained by non-linear regression method, which make the estimated curve match the measured data best. Thus, for a given yield stress, it is possible that two different sets of *k* and *n* may generate similar flow curves (rheograms). The influence of *k* and *n* will be discussed together with hydraulic parameters like frictional pressure loss and plug width in the next section. The bar chart of *k* and *n* can be found in the Appendix Figure A-1 and Figure A-2.

4.4.1.2. Hydraulic Parameter and Hole Cleaning Index

The plug width h of all the samples are plotted in Figure 4.9. For group 1 (0% bentonite), as the concentration of biopolymer increases the *h* decreases dramatically to a nadir at 0.3% and then climbs fast as more biopolymer is added. This trend is so different from the other three, which may be related to the CPC we mentioned before. If the polymer fluid is below a certain CPC value (#0-1 and #0-2 in this case), polymer particles cannot build a functional structure inside the fluid, insufficient or even no yield stress will be provided. Therefore, even they show high values of *h*, they are not because of the high yield stress but due to the low frictional pressure loss caused by low viscosity.

Moreover, with a low yield stress, no matter how wide the plug zone is, the absolute value of the viscosity (resistance to cuttings) is too low to make use of the flatter velocity profile. Thus, if we reject #0-1 and #0-2 in Figure 4.9, we can find that at lower bentonite concentration (0% to 2%) the plug zone will increase as the concentration of biopolymer increases. Meanwhile, this increasing trend will be diminished as more bentonite is added. When bentonite concentration reaches 3%, adding biopolymer can no longer flatten the velocity profile and will even cause a slight drop on *h*. In addition, instead of using bentonite-polymer mixtures, increasing bentonite concentration in pure bentonite drilling fluid we can also obtain the same or even higher value of *h*.

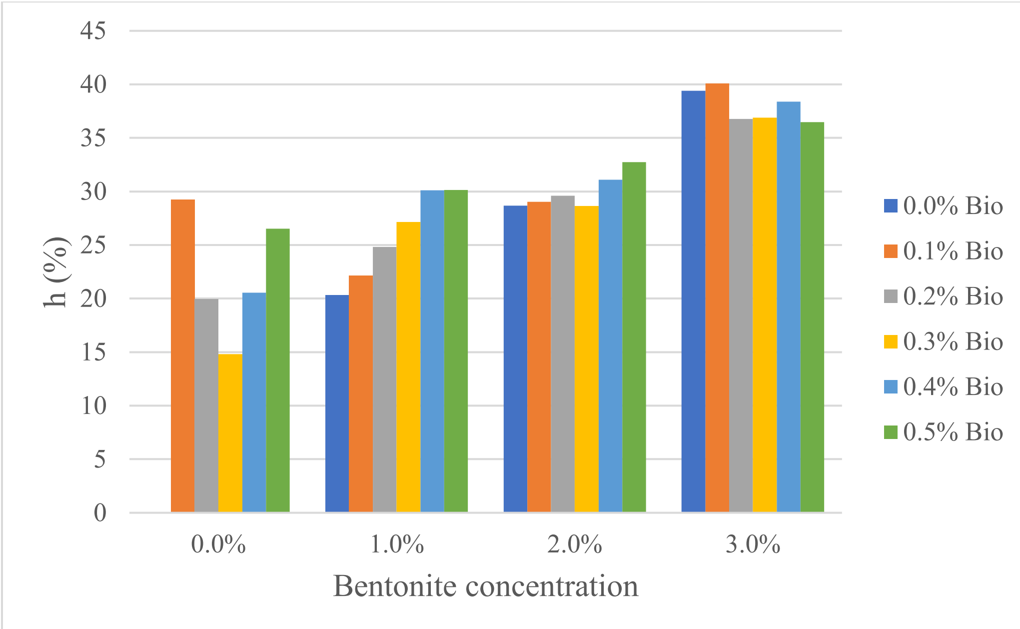


Figure 4.9 Plug width of drilling fluids

Then the conventional hole cleaning capacity index *YP*/*PV* is presented in Figure 4.10. It shows that generally the *YP*/*PV* value increases when more bentonite or biopolymers are added except for that slight drops occur when adding 0.1% biopolymer to 2% and 3% bentonite drilling fluids. When compared with plug width in Figure 4.9, since the sample #0-1 and #0-2 are invalid for plug width analysis we also ignore them in this comparison. In group 1 to 3, both *YP*/*PV* and h show a general upward trend when biopolymer concentration increases. However, for group 4 (3% bentonite), the trends of these two parameters are quite different where *YP*/*PV* decreases first then recovers gradually when more biopolymer is added while h sees a slight increase and then drops to a lower level. Both similarity and differences between these two parameters are expected since *YP*/*PV* is obtained at high-shear-rate while h is calculated based on a low flow rate condition in the annulus. The high-shear-rate properties may be correlated to low-shear-rate behavior to some extent. However, when the drilling fluids properties show more differences in these two shear rate ranges, the correlation will be further weakened. In summary, the *YP*/*PV* is partially correlated to the flatness of the velocity profile, but a higher value of *YP*/*PV* cannot always guarantee a wider plug width or flatter velocity profile.

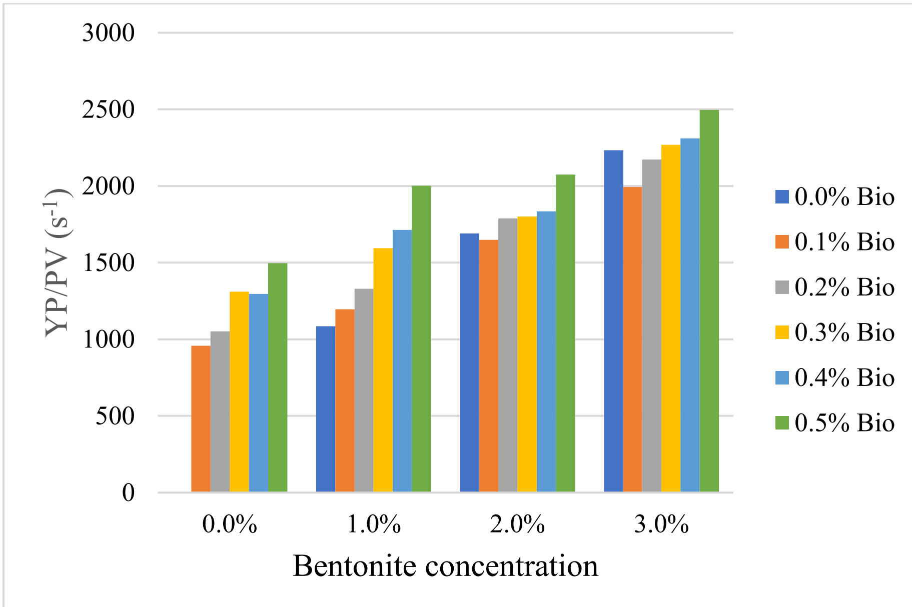


Figure 4.10 *YP*/*PV* of drilling fluids

Figure 4.11 shows the effect of bentonite and biopolymer on the frictional pressure loss, ΔP. This figure indicates that either increasing bentonite concentration or adding more biopolymers will lead to a remarkable rise of frictional pressure loss in the annulus. In addition, the CPC effect is also reflected in this graph that ΔP boosted from 60 Pa/m for 0-2 to about 256 Pa/m for 0-3. It is worth noting that both ΔP and τ_y show consistent upward trend when increasing the additive concentration in the drilling fluid. This is because ΔP is positively correlated with τ_y as we mentioned previously. In addition, since ΔP is also a function of other rheological parameters (k and n), we can still find some differences in these two graphs. For example, the τ_y of #3-4 and #3-5 is almost identical while the #3-5 shows a higher value of ΔP. This is can be explained that adding more biopolymer to #3-4 drilling fluid will raise the viscosity of the drilling fluid (higher value of k, Figure A-1) while not affecting the yield stress. This feature will be discussed together with the plug width in the next section.

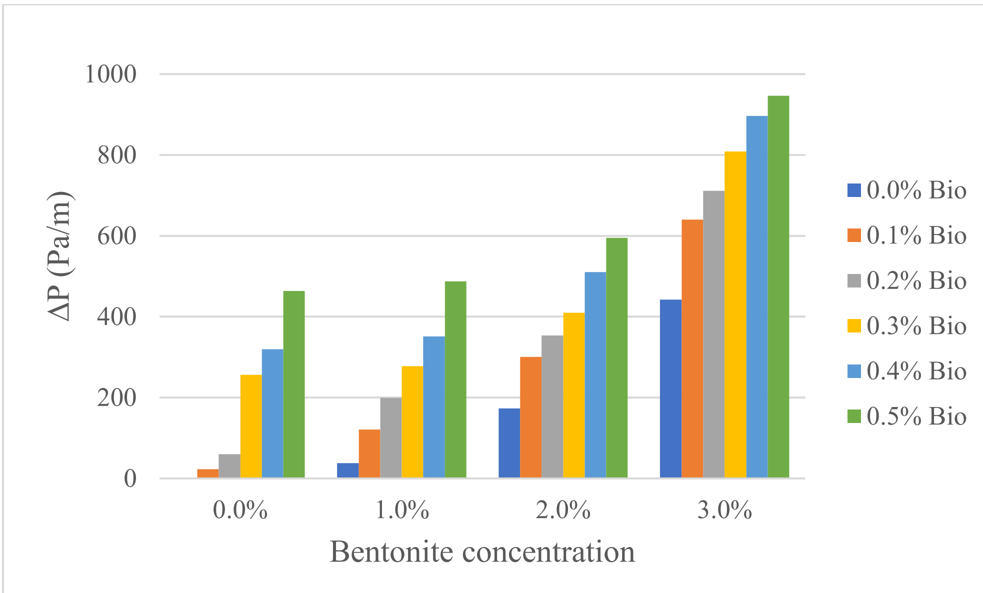


Figure 4.11 Frictional pressure loss of drilling fluids

However, either YP/PV or h is not fully qualified to be the only parameter indicating the hole cleaning capacity of the drilling fluid. Since h is the function of yield stress τ_y and frictional pressure loss, these three parameters will be presented and discussed together with their effects on the drilling fluid hole cleaning capacity.

4.4.2. Discussions

As we mentioned before that the ideal drilling fluid for good hole cleaning is expected to provide sufficient suspension (high τ_y) to cuttings under both static and dynamic conditions while inducing relatively low frictional pressure loss (lower ΔP caused by lower k and/or *n* value), which leads to wider plug width, *h* (flatter velocity profile). After the analysis of the experimental results within each group, it seems not easy to meet this requirement, since obtaining a high value of τ_y by adding more biopolymers will always induce high value of ΔP. For example, by comparing the results for sample #2-4 and #2-5 (Table 4.1). We can find that although #2-5 has a higher value of τ_y (8.3 Pa) than that of #2-4 (6.8 Pa), the high value of τ_y is also the main contributior to the high value of ΔP since *n* and *k* are quite close for these two samples. If the velocity is kept constant, sample #2-5 with higher τ_y and *h* will provide better suspension and carrying capacity to the cuttings in HDD annulus, however, the lower ΔP value of #2-4 would allow fluid velocity to be further increased. On the one hand, by increasing flow velocity, the cuttings transported in fluid #2-4 can be transported to a longer distance before settling down to the bottom which means the hole cleaning performance will be improved. On the other hand, due to the shear thinning property of the drilling fluid, an increase of velocity will raise the shear rate experienced by fluid in the annulus and further reduce the plug width which means less amount of cuttings can be carried in the high viscosity plug zone. Figure 4.12 shows that if we increase the flow rate from the original 1461 L/min to about 3187 L/min the ΔP of #2-4 will reach the level caused by #2-5 at 1461L/min and the plug width of #2-4 will be further reduced to about 26.7%. Leising and Walton (2002) once reported this in their paper that for a high LSRV fluid, doubling the flow rate will only promote the cuttings transport distance by 15%, which means high velocity indeed can improve cuttings transport, but the impact is limited. Therefore, it becomes difficult to decide whether to choose higher suspension capacity and sacrifice the sweeping capacity (#2-5) or use lower suspension for higher sweeping (#2-4). The selection of the better drilling fluid should take other factors into consideration. For example, if it is in a ground where hydrofracture is a sensitive issue, #2-4 may be preferred due to the lower frictional pressure caused by it. If it is in a rock formation which can stand high annular pressure but the pump rate is limited by either pump capacity or large annular space, we may give priority to #2-5 due to its better suspension capacity at low flow velocity.

Table 4.1 Comparison of sample #2-4 and #2-5 in rheological and hydraulic parameters

Sample No.	**n**	τ_y	**k**	**h**	**ΔP**
#		Pa	Pa•s^n	%	Pa/m
2-4	0.44	6.8	1.12	31.1	510.7
2-5	0.43	8.3	1.20	32.7	594.8

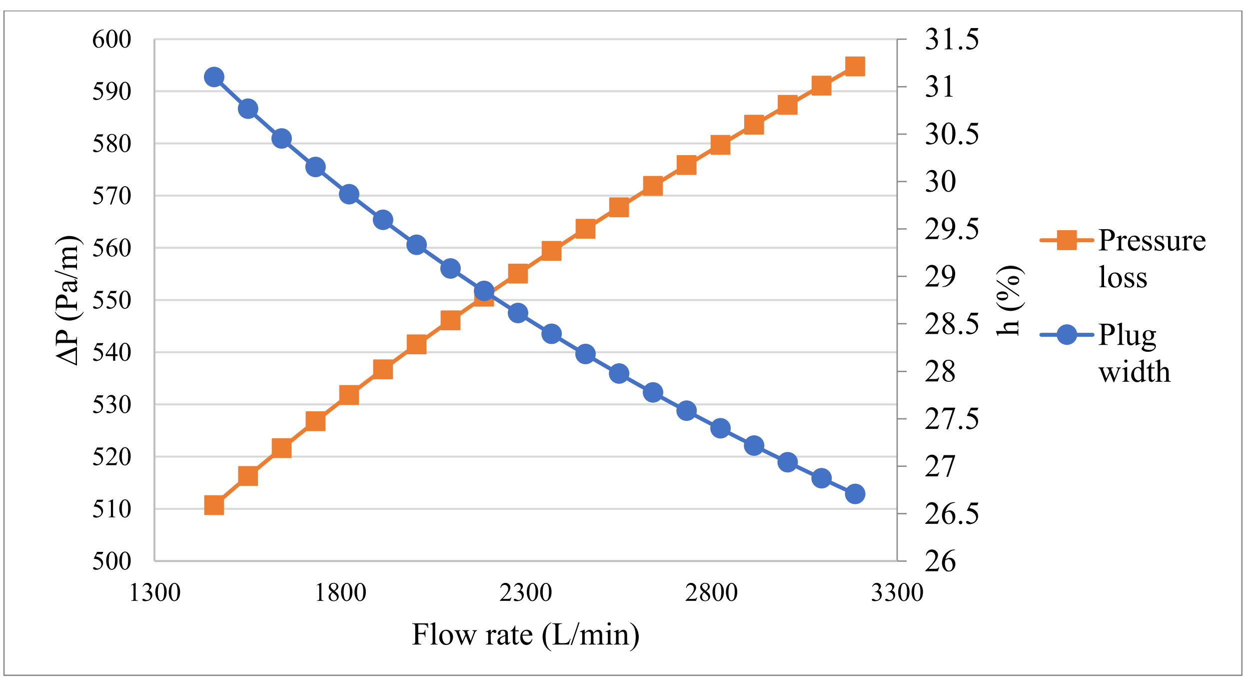


Figure 4.12 Effect of increasing flow rate when using sample #2-4

It seems quite complex to determining which fluid provides better hole cleaning capacity within each group, however, the comparison between different groups gives us a clearer conclusion. Three pairs of samples are compared to show the most three t*yp*ical situations: #1-4 and #2-2, #1-2 and #2-0 as well as #2-4 and #3-0.

For sample #1-4 and #2-2, their basic information is shown in Table 4.2. It indicates that for drilling fluids with different components may provide quite similar rheological and hydraulic properties which theoretically implies similar hole cleaning capacities.

Table 4.2 Comparison of sample #1-4 and #2-2 in rheological and hydraulic parameters

Sample No.	**n**	τ_y	**k**	**h**	**ΔP**
#		Pa	Pa•s^n	%	Pa/m
1-4	0.46	4.5	0.74	30.1	351.6
2-2	0.47	4.5	0.74	29.6	353.4

When it comes to #1-2 and #2-0 (Table 4.3), the two samples show almost the same τ_y, but #2-0 induces less *ΔP* and results in wider *h*, which is due to the lower value of *k* and *n*. This means #2-0 not only can provide better suspension to cuttings and sweeping to the cuttings bed. Furthermore, when #2-0 is selected, the lower *ΔP* allows and reasonable increase in velocity which can further improve both bed erosion and cuttings transport while still providing better suspension capacity compared with sample #1-2. In this case, sample #2-0 which contains 2% bentonite is recommended than samples #1-2 which consist of 1% bentonite and 0.2% biopolymer.

Table 4.3 Comparison of sample #1-2 and #2-0 in rheological and hydraulic parameters

Sample No.	**n**	$\boldsymbol{\tau_y}$	**k**	**h**	**ΔP**
#		Pa	Pa•s^n	%	Pa/m
1-2	0.52	2.12	0.42	24.8	199.6
2-0	0.46	2.13	0.38	28.7	173.4

When τ_y is higher, is it possible to produce even lower pressure loss at the same time? The comparison between #2-4 and #3-0 gives us a good example. Table 4.4 shows that #3-0 has a higher τ_y (7.4 Pa) than #2-4 (6.8 Pa) while still producing less ΔP, which leads to a significant improvement on h, 39.3% for #3-0 and 31.1% for #2-4. Similar to the analysis above, the Sample #3-0 is recommended with no doubt.

Table 4.4 Comparison of sample #2-4 and #3-0 in rheological and hydraulic parameters

Sample No.	**n**	$\boldsymbol{\tau_y}$	**k**	**h**	**ΔP**
#		Pa	Pa•s^n	%	Pa/m
2-4	0.44	6.81	1.12	31.10	510.7
3-0	0.46	7.47	0.53	39.39	442.2

In summary, the results show that samples with higher bentonite concentration can always provide better hole cleaning capacity compared to the mixture with less bentonite and more biopolymer in the current evaluation system. This result may be related to the bentonite used in this research. Since it is a commercial product manufactured based on Wyoming bentonite, the exact formula of this "so-called" bentonite is unknown. According to the feature that it can provide higher yield stress with relatively less concentration, some other additives may have been added to the bentonite in the manufacturing process to enhance the function of the product. Considering the large price difference between the bentonite and biopolymer additive, the bentonite used in this study is more economical effective in improving the hole cleaning capacity of the drilling fluid compared with the more expensive biopolymer.

However, the relatively low hole cleaning indices of the biopolymer in this research doesn't mean this polymer should not be select. In some situations, high solid content will cause a negative impact on the drilling process, such as forming an excessive thick filter cake, causing excessive torque and drag, reducing the rate of penetration and increasing the risk of differential sticking (Mahto and Sharma 2004). As shown in Figure 4.8 and Table 4.1, more biopolymer can provide higher yield stress and flatter velocity profile at a given flow rate which indicates higher cuttings suspension and carrying capacity when pressure loss is not the primary concern. Also, results shown in Table 4.2 suggested that by adding more biopolymer we can obtain similar properties of drilling fluids with a lower concentration of bentonite.

4.5. Conclusions

To investigate a new evaluation method of drilling fluid hole cleaning capacity in HDD, the effect of drilling fluid properties as well as other factors influencing the hole cleaning performance was reviewed and discussed. An attempt is made to analyze drilling fluid hole cleaning capacity based on the Herschel-Bulkley model and velocity profile concept. A series experiments were conducted to investigate the effect of a biopolymer additive on the rheological and hydraulic behavior of bentonite water-based drilling fluid in terms of modifying their hole cleaning capacity in HDD annulus.

The conclusions can be summarized as:

(1) The high yield stress of drilling fluid can provide goodsuspension to the cuttings under both static and dynamic conditions since it is correlated with the inner structure of the drilling fluid. Plug width indicates the area in the annular space that can provide good suspension to the cuttings due to the low shear rate and high viscosity in this region. Yield stress and plug width were used together to indicate the suspension capacity of drilling fluid.

(2) The sweeping capacity of water-based drilling fluid depends on the its viscosity. Drilling fluids with higher viscosity will exert extra compressive force on the cutting particles, which need to be pumped at higher flow rate to initiate the bed erosion compared to lower viscosity fluids. The better sweeping capacity can be indicated by lower frictional pressure loss caused by the fluid under a given flow rate.

(3) The low flow rate in HDD annulus will largely reduce the erosion to the cuttings bed due to flow of drilling fluid. The mechanical agitation of drill pipe rotation on the cuttings bed can significantly improve the bed erosion and compensate the diminished sweeping capacity of drilling fluid due to low flow velocity.

(4) High frictional pressure loss due to high viscosity (high value of rheological parameters) is not preferred in HDD since it not only indicates a low drilling fluid sweeping capacity but also raises the risk of hydrofracture and limits the allowable flow rate. Furthermore, relatively lower frictional pressure loss caused by the low value of *k* and *n* value is good for improving the sweeping capacity and flattening of the velocity profile.

(5) High yield stress and low value of k and n can provide flatter velocity profile (wider plug width), which is good for hole cleaning due to its increased width of the high viscosity plug zone and, therefore, can provide better suspension to cuttings under flow state and shear-thinning area near the wall which also reduces the frictional pressure loss.

(6) The increase of bentonite or biopolymer concentration can both enhance the suspension capacity of the drilling fluid. However, the bentonite used in this research always shows superior hole cleaning performance than the biopolymer by inducing lower frictional pressure loss while providing similar or higher suspension capacity.

Since this evaluation method is mainly based on previous theoretical and experimental researches, and the analysis of the drilling fluid hole cleaning capacity on only based on laboratory rheological property tests, the conclusions need to be verified by further cuttings transport tests using lab scale flow loop tests and field tests in the future. Also, since the rheological parameters play very important roles in this evaluation system, the accuracy of the measuring method can be improved by adopting high-precision apparatus like Brookfield rheometers which can measure the shear stress at as low shear rate as 0.06 s^{-1} and dynamic oscillatory rheometers that measure elastic properties of drilling fluid under vibration.

Chapter 5: Conclusions and Future Research

5.1. Conclusions

In this thesis, a review on hole cleaning in horizontal wells and HDD was presented. Rheological tests were conducted on drilling fluids with different concentration of bentonite and biopolymer. The effects of these additives on hole cleaning related the rheological and hydraulic parameters were determined. A new evaluation method based on the Herschel-Bulkley model was presented to compare the hole cleaning capacity of drilling fluids in HDD application. The most important conclusions are highlighted as follow:

(1) The influential factors for hole cleaning performance in HDD annulus were introduced. The high controllable factors: flow velocity, drilling fluid rheological property and drill pipe rotation were discussed in detail. The effect of these three factors is highly dependent on each other. The unique features of HDD process, like high inclination, low flow velocity and high sensitivity to annular pressure, may change the priority of the influential factors, the criteria of cuttings transport modeling as well as evaluation of the drilling fluid hole cleaning capacity.

(2) The hole cleaning capacity of drilling fluid were divided into two components: suspension capacity indicating the capacity of suspending the cuttings in the fluid and sweeping capacity representing the capacity of eroding the cuttings bed due to fluid flow.

(3) The high yield stress of drilling fluid can provide good suspension to the cuttings under both static and dynamic conditions since it is correlated with the inner

structure of the drilling fluid. The plug width is the width of the unsheared portion of the velocity profile in the annulus. It indicates the area in the annular space that can provide good suspension to the cuttings due to the low shear rate and high viscosity in this region. Yield stress and plug width were used together to indicate the suspension capacity of drilling fluid.

(4) The sweeping capacity of a viscoelastic drilling fluid depends on its viscosity. Drilling fluids with a higher viscosity will exert an more compressive force on the cutting particles, which need to be pumped at a higher flow rate to initiate the bed erosion compared to lower viscosity fluids and show less sweeping capacity. The better sweeping capacity can be indicated by the lower frictional pressure loss caused by the lower viscosity of the fluid under a given flow rate.

(5) Low frictional pressure loss caused by low viscosity will also reduce the risk of hydrofracture while allows higher flow rate to be pumped to enhance cuttings bed erosion and cuttings transport distance.

(6) At low flow velocity, the drill pipe rotation can significantly improve the hole cleaning performance through mechanical agitation to the cuttings bed. This can also compensate the drilling fluid's weak erosion to the cuttings bed due to low flow velocity. Suspension capacity of drilling fluid become more important especially when the flow velocity is too low to provide effective bed erosion.

(7) In the first experimental stage, pure bentonite drilling fluids with various bentonite concentrations were used. The increase of bentonite concentration provided higher suspension capacity (higher τ_y and h) and lower sweeping capacity (higher viscosity and ΔP). The selection of bentonite concentration should depend on multiple

conditions like flow velocity, pump capacity and allowable annular pressure. The comparison between *YP/PV* and h indicated that the higher value of conventional hole cleaning index *YP/PV* may be related to higher suspension capacity in this case but cannot guarantee a flatter velocity profile.

(8) In the second experimental research which involved both bentonite and biopolymer. τ_y and ΔP keep increasing with the increase of bentonite or biopolymer concentration. When comparing the hole cleaning capacity of two samples, there were generally two situations. When fluid A has higher τ_y and ΔP than fluid B, which is similar to the situation in pure bentonite tests, the selection of drilling fluid should depend on the real situation, including the requirements and limitations. When fluid A has equal or higher τ_y and lower ΔP than fluid B, fluid A is recommended. Because the higher τ_y and lower ΔP result in wider plug width which indicates better suspension capacity for fluid A. Lower ΔP not only indicate better sweeping capacity but also reduce the risk hydrofracture and allows a potential increase in flow velocity.

(9) Samples with higher bentonite concentration and lower biopolymer concentration usually showed better hole cleaning capacity (higher τ_y and lower ΔP). Considering the huge price difference between the bentonite and biopolymer, the bentonite used in this study is more economically effective in improving hole cleaning capacity of the drilling fluid.

5.2. Future research

Since the yield stress and low-shear-rate properties are found to be of great importance in drilling fluid hole cleaning capacity by affecting cuttings suspension in both static and dynamic states, more precise apparatuses are recommended in the future research. These apparatuses can provide more reliable data through direct measurements at the low shear rate/strain rather than the approximate values obtained by currently used non-linear regression method.

Flow loop which can simulate cuttings transport in HDD annulus needs to be built. The effect of low flow velocity and drill pipe rotation should be verified using different drilling fluids. The proper yield stress for a given annular condition should be investigated to guide the drilling fluid selection in the field.

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Appendix

Table A-1 Rheological parameters of Xanthan Gum and bentonite drilling fluids

Bent. Conc.	Additive conc.	Sample No. (#)	Bingham plastic model			Herschel-Bulkley model		
			PV	*YP*	*YP*/*PV*	n	τy	k
			Pa•s	Pa	s^{-1}		Pa	Pa•s^n
0%	0.1%	0-1	0.0020	1.0	478.8	0.7168	0.2890	0.0194
	0.2%	0-2	0.0050	2.9	574.6	0.6143	0.5131	0.1089
	0.3%	0-3	0.0130	11.5	883.9	0.4858	1.6262	0.8351
	0.4%	0-4	0.0155	12.7	818.6	0.4971	2.8186	0.8460
	0.5%	0-5	0.0160	16.3	1017.5	0.4722	5.2694	1.0783
1%	0.0%	1-0	0.0025	1.5	606.5	0.5508	0.3299	0.0839
	0.1%	1-1	0.0070	5.0	718.2	0.5490	1.1484	0.2536
	0.2%	1-2	0.0090	7.7	851.2	0.5173	2.1240	0.4231
	0.3%	1-3	0.0090	10.1	1117.2	0.4754	3.2283	0.6213
	0.4%	1-4	0.0095	11.7	1234.8	0.4586	4.5363	0.7375
	0.5%	1-5	0.0110	16.8	1523.5	0.4387	6.2902	1.0980
2%	0.0%	2-0	0.0050	6.1	1213.3	0.4646	2.1321	0.3791
	0.1%	2-1	0.0090	10.5	1170.4	0.4754	3.7392	0.6213
	0.2%	2-2	0.0095	12.4	1310.4	0.4661	4.4857	0.7368
	0.3%	2-3	0.0105	13.9	1322.4	0.4379	5.0316	0.9887
	0.4%	2-4	0.0120	16.3	1356.6	0.4354	6.8077	1.1151
	0.5%	2-5	0.0120	19.2	1596.0	0.4346	8.3490	1.2019
3%	0.0%	3-0	0.0080	11.5	1436.4	0.4579	7.4658	0.5344
	0.1%	3-1	0.0120	18.2	1516.2	0.5323	10.9929	0.5189
	0.2%	3-2	0.0130	22.0	1694.2	0.4708	11.2209	0.9850

0.3%	3-3	0.0135	24.2	1791.1	0.4445	12.7848	1.2375
0.4%	3-4	0.0145	26.6	1832.6	0.4664	14.7561	1.1272
0.5%	3-5	0.0140	28.2	2017.8	0.4144	14.7986	1.6847

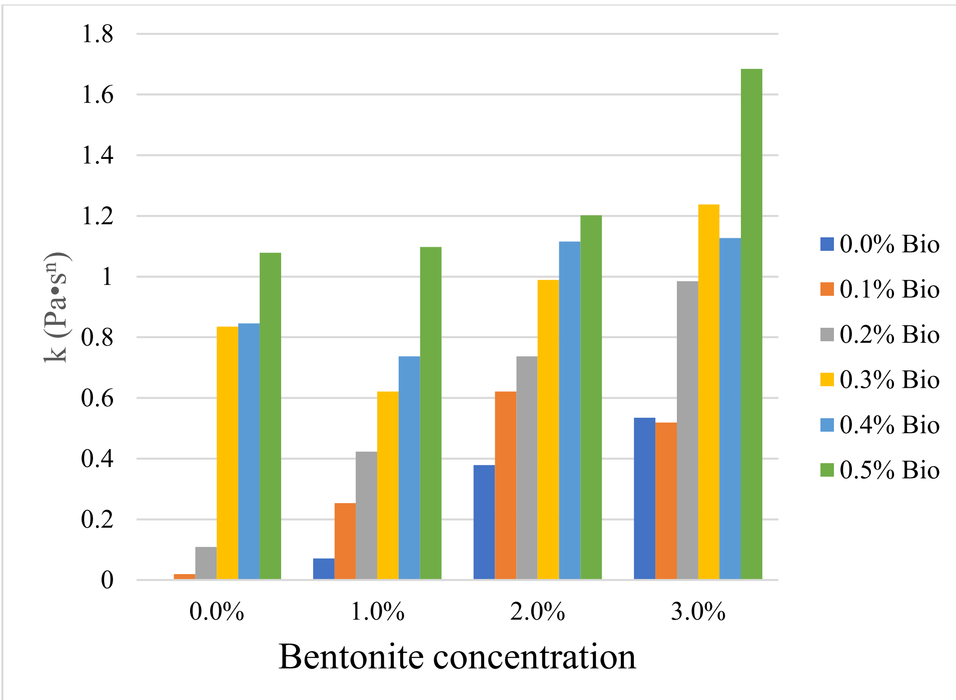

Figure A-1 Herschel-Bulkley consistency index (k) of drilling fluids

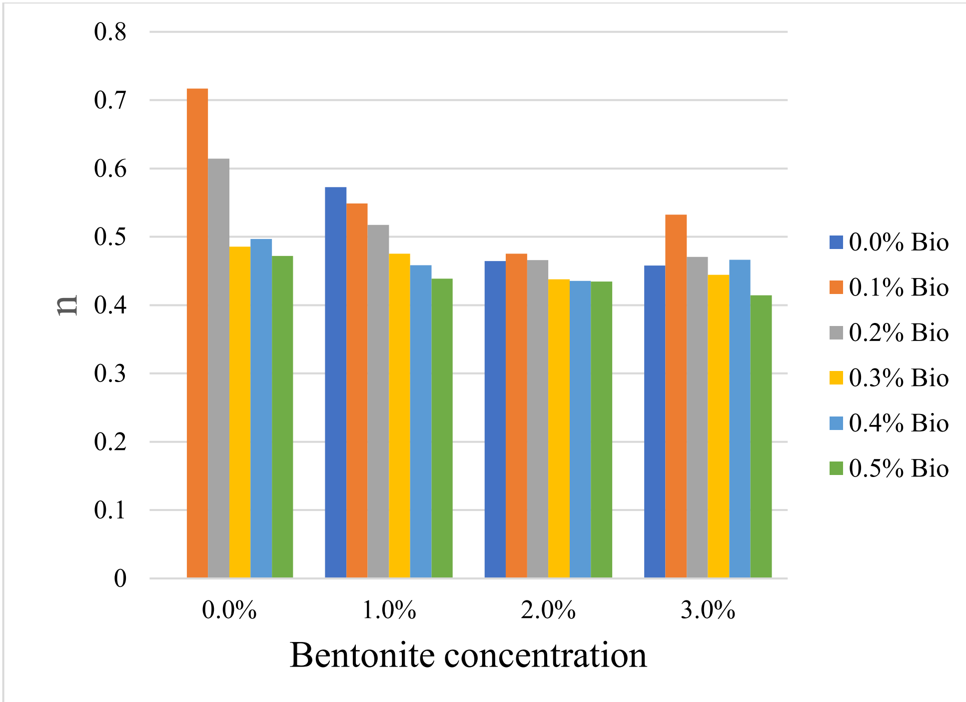

Figure A-2 Herschel-Bulkley flow behavior index (n) of drilling fluids