NANOSILICA-ENHANCED WATER-BASED DRILLING MUD FOR HOLE CLEANING IN INCLINED WELLS

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A thesis submitted in fulfilment of the

requirements for the award of the degree of

Doctor of Philosophy

School of Chemical and Energy Engineering

Faculty of Engineering

Universiti Teknologi Malaysia

JUNE 2019

Special Dedication to all my family members,

especially to my parents,

my friends and my faith.

For all the love, care, and support given to me.

ACKNOWLEDGEMENT

First, I would like to thank God for his blessings and for answering my prayers throughout the course of my Doctorate program in Universiti Teknologi Malaysia. I would not be able to complete this research paper on time and fulfill the requirements without my faith.

A special thanks to my compassionate supervisors, Associate Professor Issham Ismail and Dr. Wan Rosli Wan Sulaiman, for their guidance and teaching that pushed me to be a better learner and a better person. I feel that I have grown to be wiser and more dedicated to my work because they believed that I can accomplish greatness with hard work and goals. Their willingness to guide me and overseeing the progress I made was crucial for me to be on the right track with my research. Their help and advice helped me a great deal throughout my journey.

I would also like to express my gratitude to my family members back home who gave me motivation and for lifting my spirits upon completing my Doctorate. A special thanks to my mother who is supporting me all the way and molded me into the person I am today. I could not achieve half of what I have achieved today if it wasn't for her love, care, and support. Not forgetting my sister and her loving family who are always there to cheer me on.

Last but not least, thanks to all my friends especially to Norhafizuddin Husein for helping me to get through the difficult times. The experiences and knowledge gained throughout this journey proved to be invaluable in the process of equipping me to face future challenges.

ABSTRACT

Inadequate hole cleaning often leads to challenges in drilling operations such as poor cuttings lifting that causes pipe sticking, losing tools, and difficulties in liner/casing placements. Designing a drilling mud with improved rheological properties that are facing minimal degradation under high temperature conditions would be a better solution to increase cuttings transportation efficiency. Static tests which included rheological properties, fluid loss, and fluid flow behaviour of the drilling mud with and without nanosilica were examined according to API standards. This study also involved dynamic tests which investigated the performance of nanosilica in degraded and non-degraded water-based drilling muds to improve cuttings lifting in inclined drilling operations. This research uses a jacketed mixing tank with a capacity of 200 litres and an operating temperature of up to 482°F (250°C) to degrade drilling mud with and without nanosilica before testing them at ambient condition in a flow loop. Simulated cuttings of irregular shape and sizes ranging from 1.4 to 4.0 mm were used. Different inclination angles (0, 30, 60, and 90°) have been considered in the dynamic tests with and without pipe rotation (120, 150, and 180 rpm) to simulate the drilling conditions in a wellbore. It was found that the presence of nanosilica has increased the cuttings transportation efficiency (CTE) in all experiments. Results indicate that the presence of nanosilica in mud increases the colloidal interactions with cuttings and contributes to improvements in CTE by 30.8 to 44%. At elevated temperatures, 12 ppg muds performed better than 9 ppg muds. However, after adding the optimum concentration of nanosilica of 1.0 ppb (by weight), the CTE improvement for 9 ppg muds was higher than that for the 12 ppg muds. The presence of nanosilica improves the CTE at elevated temperatures because the distribution of nanosilica in the mud is able to withstand the heat in high temperature conditions thus improving CTE when comparing to mud without nanosilica. The introduction of nanosilica in water-based drilling fluids shows promising results in hole cleaning process which will enable them to be used in extended reach drilling operations.

ABSTRAK

Pembersihan lubang penggerudian yang tidak mencukupi sering membawa kepada cabaran dalam operasi penggerudian seperti pengangkatan keratan batu yang tidak memuaskan akan menyebabkan paip melekat, kehilangan alat, dan kesulitan dalam penempatan pelapisan/kelongsong. Mereka bentuk lumpur penggerudian dengan sifat-sifat reologi yang lebih baik yang mengalami kemerosotan minimum di bawah keadaan suhu tinggi akan menjadi penyelesaian terbaik untuk meningkatkan kecekapan pengangkutan keratan. Ujian statik yang merangkumi sifat-sifat reologi, kehilangan bendalir dan kelakuan aliran bendalir lumpur penggerudian tanpa nanosilica dan dengan nanosilika diperiksa mengikut piawaian API. Kajian ini juga melibatkan ujian dinamik yang menyiasat prestasi nanosilika dalam lumpur penggerudian berasaskan air yang terdegradasi dan tidak terdegradasi untuk meningkatkan penggerudian dalam operasi penggerudian condong. Kajian ini menggunakan tangki pencampuran berjaket dengan kapasiti 200 liter dan suhu operasi sehingga 482 °F (250 °C) untuk merosotkan lumpur penggerudian dengan nanosilika dan tanpa nanosilika sebelum menguji mereka pada keadaan ambien didalam gelung aliran. Bentuk keratan yang digunakan tidak bersaiz tetap dan saiz keratan adalah bersaiz antara 1.4 hingga 4.0 mm. Sudut kecondongan yang berlainan (0, 30, 60, dan 90 °) telah dipertimbangkan dalam ujian dinamik tanpa putaran paip dan dengan putaran paip (120, 150, dan 180 rpm) untuk mensimulasikan keadaan penggerudian dalam lubang sumur. Kajian mendapati bahawa kehadiran nanosilika telah meningkatkan kecekapan pengangkutan keratan (CTE) dalam semua eksperimen. Keputusan menunjukkan bahawa kehadiran nanosilika dalam lumpur meningkatkan interaksi koloid dengan keratan dan menyumbang kepada peningkatan CTE sebanyak 30.8 hingga 44%. Pada suhu tinggi, lumpur 12 ppg mempamerkan prestasi lebih baik daripada lumpur 9 ppg. Walaubagaimanapun, selepas menambah kepekatan nanosilica optimum sebanyak 1.0 ppb (berat), peningkatan CTE untuk lumpur 9 ppg lebih tinggi daripada lumpur 12 ppg. Kehadiran nanosilika meningkatkan CTE pada suhu tinggi kerana taburan nanosilica dalam lumpur dapat menahan panas dalam keadaan suhu yang tinggi sehingga meningkatkan CTE jika dibandingkan dengan lumpur tanpa nanosilika. Pengenalan nanosilika dalam bendalir penggerudian berasaskan air menunjukkan prestasi baik dalam proses pembersihan lubang yang akan membolehkan mereka digunakan dalam operasi penggerudian jangkauan lanjutan.

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LIST OF ABBREVIATIONS

API	-	American Petroleum Institute
ATR	-	Attenuated Total Reflectance
CTE	-	Cuttings Transportation Efficiency
CuO	-	Copper Oxide
EDL	-	Electrical Double Layer
FTIR	-	Fourier-transform-infrared
GBDF	-	Gas-based Drilling Fluid
GS	-	Gel strength
HPHT	-	High Pressure High Temperature
KCl	-	Potassium Chloride
MPa	-	Mega Pascal
Mt	-	Montmorillonite
MWCNT	-	Multiwalled Carbon Nanotube
NaCl	-	Sodium Chloride
NPBM	-	Nanoparticles Based Brine Mud
OBDF	-	Oil-based Drilling Fluid
Pal	-	Palygorskite
PSBR	-	Polystyrene-Butadiene Rubber Copolymer (Oil Base Mud)
PV	-	Plastic Viscosity
RPM	-	Revolution per Minute
RT	-	Room Temperature
SDFL	-	Polymer Based Nanosilica Composite with Core-shell
SEM	-	Scanning Electron microscope
TGA	-	Thermogravimetric Analysis
WBM	-	Water-based Mud
WBDF	-	Water-based Drilling Fluid
YP	-	Yield Point
ZnO	-	Zinc Oxide

LIST OF SYMBOLS

A0	-	9 ppg basic mud
A1	-	9 ppg mud with 0.5 ppb nanosilica
A2	-	9 ppg mud with 1.0 ppb nanosilica
A3	-	9 ppg mud with 1.5 ppb nanosilica
B0	-	12 ppg basic mud
B1	-	12 ppg mud with 0.5 ppb nanosilica
B2	-	12 ppg mud with 1.0 ppb nanosilica
B3	-	12 ppg mud with 1.5 ppb nanosilica
CoF	-	Coefficient of Friction
F_g	-	Gravitational force
F_d	-	Drag force
F_f	-	Friction force
F_c	-	Cohesive force
F_{ga}	-	Resolved gravity force
F_L	-	Lift force
h	-	Thickness of filtration cake
ID	-	Inside diameter
K	-	Consistency index
k	-	Permeability
μ	-	Viscosity (cp)
μS	-	Microsiemens
μ_∞	-	Plastic viscosity (cp)
OD	-	Outside diameter
τ	-	Shear stress (Dynes/cm^2)
τ_0	-	Yield stress (Dynes/cm^2)
vs.	-	Versus
γ	-	Shear rate (1/sec)
Q_f	-	Volume of filtrate (cm^3)

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CHAPTER 1

INTRODUCTION

1.1 Background

Oil and gas exploration have been improved by new levels of technologies where deeper and harsher environments are being drilled more than ever before. Drilling fluids play a vital role in drilling operations, such as cooling and lubricating the bit and drill string, cleaning the bottom of the hole, controlling formation pressure, improving drilling rate, among others (Bourgoyne *et al.*, 1986). In recent years, drilling in harsh conditions, such as extended reach and deep-water drilling operations, highlighted the unsuitability of conventional muds for the successful drilling and hole cleaning process. Therefore, there is a demand for new drilling fluids that can perform efficiently in such conditions. Oil producers and service companies have been investigating more effective ways to tackle challenging environments in order to drill and produce in a safe and feasible manner. For example, oil-based drilling fluids treated with micronized barite were tested in the North Sea (Kageson-Loe *et al.*, 2007). Oil-based mud showed promising performance in shale inhibition, bit lubrication and torque reduction (Caldarola *et al.*, 2016). However, drilling with oil-based mud is associated with high costs of procurement and toxic waste management. Thus, extensive research has gone into improving water-based mud because of their low cost and environmentally friendly attributes (Rafati *et al.*, 2017).

Water was the first drilling fluid used in drilling operations (Brantly, 1961). However, water is not able to suspend cuttings in static conditions, build an impermeable layer on permeable formations, and also it is not dense enough to balance formation pressure. Today, water-based muds contain several additives. These include alkalis, salts, surfactants, organic polymers in colloidal solution, and various insoluble weighting materials such as barite and clay. The selection of additives is based on the type of formation to be drilled, dispersive materials in the formation, and cost. According to Apaleke *et al.* (2012), increased drilling activities provided a market for heavy muds made by adding heavy minerals to increase mud density for pressure control, and this led to improvements of water-based mud. However, there are still significant limitations of water-based mud in their stability and cuttings lifting ability.

Hall *et al.* (1950) stated that the removal of cuttings and sloughs is one of the most important functions of drilling fluids. According to Hakim *et al.* (2018), drilled cuttings removal is critical especially in horizontal wells. In addition to reducing rates of penetration by accumulated cuttings in the wellbore, inefficient hole cleaning increases the possibility of stuck pipe. Wellbore cleaning is highly affected by mud rheology. However, previous studies showed contradictory findings regarding mud rheology and their performance in the hole cleaning process. A study done by Ford *et al.* (1990) showed that high viscosity values increase cuttings lifting performance in inclined wellbores. Kelessidis & Bandelis (2007) however concluded that the performance of hole cleaning worsened when the viscosity of drilling mud was increased in horizontal wells. This contradiction might be due to the transition of turbulent flow to laminar flow when viscosity increases, which deteriorates the performance of drilling fluid to clean the wellbore. In another study, Walker & Li (2000) confirmed the findings of Kelessidis & Bandelis (2007), provided that the flow regime is turbulent. They reported this condition works mainly in horizontal or highly deviated wellbores. They recommended that for vertical or slightly deviated wellbores, a viscous drilling mud with a laminar flow regime should be used.

Hole inclination plays a tremendous role in determining the performance of drilling mud to carry cuttings out of a borehole. There are many complex well trajectories targeting deep reservoirs. Typical well designs in extended reach drilling operations have high inclination and dog-leg severity to reach pay zones. Many researchers have reported that inclination angles between 40° and 60° (deviation from vertical position) are critical angles where most of the accumulation of cuttings happens and it is difficult to transport cuttings out of the hole (Seeberger *et al.*, 1989; Peden *et al.*, 1990; Brown *et al.*, 1989; Onuoha *et al.*, 2015; Ogunrinde & Dosunmu, 2012). The formation of cuttings beds is one of the most common problems that occurs at critical angles when drilling fluid fails to transport cuttings up to the surface. In deviated or horizontal drillings, transportation of cuttings is mainly influenced by net vertical forces. If the net vertical force is downwards, there will be formation of cuttings bed in the annulus.

The cuttings' shape and size determine their dynamic behaviour in a flowing drilling mud. The properties and dimensions of the cuttings in drilling fluids affect their removal from downhole to the surface. There are different findings on the effect of cuttings size on the hole cleaning process. Martins *et al.* (1996) found that cuttings with bigger sizes are difficult to transport to the surface; other researchers (Peden *et al.*, 1990; Walker & Li, 2000) stated that cuttings with smaller sizes are the most difficult to transport. However, if the viscosity of the drilling mud and rotating speed are high, cuttings that are smaller in size can be transported efficiently to the surface (Sanchez *et al.*, 1999). Furthermore, Ford *et al.* (1990) observed that as cuttings size decrease, the minimum transport velocity required for cuttings rolling and suspension decreases. This means, in terms of minimum transport velocity, smaller cuttings are easier to transport.

Duan *et al.* (2009) suggested that different fluids are required for different purposes. Water is usually required for cleanout and polymer solutions are required for drilling operations. They also reported that the increasing number of highly inclined and horizontal wells through unconsolidated reservoirs signifies the challenge for the transportation of smaller cuttings during drilling operations. Based on the results from a study conducted by Ozbayoglu *et al.* (2004) the most effective drilling parameter in the development of cuttings bed is the flow rate of mud, or the annular fluid velocity. As the flow rate increases, cuttings bed development can be prevented. Therefore, the most effective hole cleaning process is during turbulent flow regime, which reduces the chance of cuttings bed development by efficient cuttings transportation (Piroozian *et al.*, 2012). Other researchers like Sifferman *et al.* (1974) and Larsen *et al.* (1997) found that the acceptable annular velocity for cuttings transport for typical drilling mud is in the range of 1 to 4 ft/sec. The annular velocity of fluid depends pump rate and the hole diameter. Flow rate is usually monitored to ensure the risk of formation of cuttings beds is minimized in dynamic conditions.

In drilling operations, the drill string has the tendency to rest on the low side of the borehole because of gravity, especially in inclined sections of a hole. This creates an eccentric narrow gap in the annulus below the pipe, where fluid velocity will be extremely low. Effectively, the drilling fluids' ability to transport cuttings to the surface in this part of the annulus will be low. As eccentricity increases, the particle and fluid velocities would decrease in the narrow gap, especially in high viscosity fluids. However, such adverse impacts on the hole cleaning process may be unavoidable because the pipe eccentricity is governed by well trajectories during drilling operations. Therefore, as pipes shift away from concentric status, cuttings removal efficiency decreases (Tomren *et al.*, 1986).

Drilling in deeper formations adds more challenges for drilling fluid to lift drilled cuttings effectively to the surface. Conventional bio-polymers are no longer capable of maintaining rheologically stable fluids at temperatures above 300°F. Shah *et al.* (2010) stated that drilling fluids exhibit sagging behaviour under extreme conditions. Drilling fluids also exhibit syneresis which is known as the expulsion of liquid from the gel structure under these circumstances.

Dynamic tests on mud performance in a flow loop system are especially crucial, because results obtained from static tests (rheological properties) do not necessarily translate into dynamic performance of drilling fluids. An experimental study conducted by Wang *et al.* (1995) showed that drill string rotation could significantly reduce cuttings bed height. Rotational speed is more effective in inclined wells compared to vertical wells (Tomren *et al.*, 1986; Sanchez *et al.*, 1999; Yu *et al.*, 2007). This indicates that cuttings transportation at the narrow side of an eccentric wellbore can be improved by rotating drill pipes. Sifferman *et al.* (1992) concluded that at highly deviated wellbores, low rates of penetration and small cuttings are the most desirable conditions for using pipe rotation effectively. Formation of Taylor vortices (beyond a specific rotational speed) can further assist in improving the lifting efficiency in horizontal sections (Sanchez *et al.*, 1999). Therefore, for the removal of small drilled cuttings, the drill pipe rotation factor is a very important parameter to be considered (Duan *et al.*, 2006; Saeid & Busahmin 2016).

To analyse dynamics of flow in the hole cleaning process, Ettehadi *et al.* (2015) conducted an investigation where different amounts of cuttings were injected into an experimental rig with various air and water flow rates in a multiphase flow system. They compared experimental data with developed models and found that frictional pressure losses can be predicted with reasonable accuracy. In another study, Ogunrinde & Dosunmu (2012) investigated critical factors affecting cuttings removal and bit hydraulics in different inclination angles. They developed a model to determine the optimum flowrate and rate of penetration to reduce non-productive time. Similarly, Guan *et al.* (2016) studies different hole cleaning parameters using the multi-dimensional ant colony algorithm to optimize drilling operation in horizontal wells. They concluded that hole cleaning for horizontal wells can be improved by increasing the flow rate and pressure-bearing capacity of the system. Recently, Boyou *et al.*, (2018) used polymer beads (polypropylene) in water-based drilling fluids to improve its lifting capability of muds. They examined the cuttings transport efficiency using different sizes of cuttings in inclined static annuli and found that small cuttings were transported more efficiently compared to large cuttings due to drag force on cuttings introduced by polymer beads. However, as the cutting sizes approached the size of beads, cuttings transport efficiency decreased.

In recent years, the application of nanomaterials has been on the rise, especially within the scientific community. There is broad range of applications for nanomaterials in the fields of drilling fluids and reservoir protection that is beneficial for petroleum development and production (Li *et al.*, 2012). There are studies that show significant rheological improvements of water-based drilling fluids due to the presence of nanomaterials (Abdo & Haneef, 2013; Cedola *et al.*, 2016; Noah *et al.*, 2016; Samsuri & Hamzah, 2011; Sharma *et al.*, 2012; Smith *et al.*, 2018; William *et al.*, 2014; Yang *et al.*, 2015). A study reported by Yasir (2016) found that nano drilling fluids performed better in terms of bit cooling, reduced torque and drag, enhanced viscous behaviour and low friction factors compared to conventional drilling fluids. Furthermore, improvements in thermal stability up to 160°C were reported by different studies, in which nanoparticles such as silica, carbon nanotubes and aluminium oxide were added to water-based drilling fluids (Cai *et al.*, 2012; Kang *et al.*, 2016; Smith *et al.*, 2018; Yang *et al.*, 2015; Yuan *et al.*, 2013). Hoelscher *et al.* (2012) reported physical plugging of nanometer-sized Marcellus and Mancos shale pores by using nanosilica which resulted in reduced pressure transmission in shale. Many studies have reported the use of nanomaterials for filtration control, rheological enhancement etc. that are beyond the scope of this study. Overall, nanoparticles have been used to overcome a variety of issues related to drilling fluids, such as enhancing the thermal stability of mud at high-temperature conditions, reducing filtrate volume and thickness of mud cake, modifying friction factor, among others; a detailed review of these studies can be found elsewhere (Rafati *et al.*, 2017; Sharma *et al.*, 2016). Although much literature has focused on the use of nanoparticles to enhance the rheological properties of drilling fluids but there is no investigation on the enhancement of cuttings transport in wellbore during hole cleaning process. There is also no reported investigation of degraded drilling fluids with nanoparticles for wellbore cleaning.

In this study, important factors in hole cleaning processes are discussed, and an experimental flow loop simulator was modified to analyse the impact of nanoparticles on cuttings transport efficiency in directional drilling operations. The dynamic performance of degraded drilling mud after heated at different temperatures with and without nanoparticles is also analysed. The setup is capable of simulating the hole cleaning process in the annulus with different rotational speeds and inclinations. Furthermore, different cuttings sizes are studied to understand the effect of cuttings size on dynamics of flow. It is assumed there is no pipe eccentricity and mud properties remain unchanged during the hole cleaning process. Through analysis of the results, the performance of nano-enhanced water-based muds can be summarised.

1.2 Problem Statement

In recent years, drilling for oil and gas exploration encounters complex and harsh conditions in deep and ultra-deep formations such as high temperature and high pressure (HTHP) (Yang *et al.*, 2017). API data show that the cost of drilling increases exponentially with increasing depth (Smith, 2001). Offshore exploration drilling and appraisal wells in the development of an oilfield are among the highest capital costs up to 60% (US Energy Information Administration, 2016). The success of any drilling operation highly depends on the performance of drilling fluids especially in extended reach and deep-water drillings (Smith *et al.*, 2018).

Wellbore cleaning has been an integral part of a drilling operation in oil and gas exploration and field development. Challenges of wellbore cleaning in deep and harsh environments increase due to mud degradation in high temperature conditions (Bland *et al.*, 2006; Bybee, 2001; Elward-Berry & Thomas, 1994). Consequently, the degraded mud loses its carrying capacity over time and forces the oil operator to take a longer time to completely drill a hole. This means the oil operator experiences higher non-productive time and cost for drilling operation, thus affecting its profitability (Shaughnessy *et al.*, 2003). Therefore, a better understanding of how degraded mud affects cuttings lifting performance is a key component for deep hole drilling in extreme conditions.

In recent years, oil-based muds are often required for deep drilling in harsh conditions because of their stability in high pressure and high temperature environments. However, due to their challenging toxic waste management and high cost of procurement and handling, extensive research works are re-aligned towards improving water-based mud performance in such conditions (Amani *et al.*, 2012; Srivatsa & Ziaja, 2011).

There are a lot of studies focusing on improving water-based muds by adding nanoparticles, however all of the previous studies have only included tests in static conditions (Abdo & Haneef, 2013; William *et al.*, 2014; Yang *et al.*, 2015; Noah *et al.*, 2016; Nasser *et al.*, 2013; Mao *et al.*, 2015; Baghbanzadeh *et al.*, 2012; Samsuri & Hamzah, 2011). Thus, a research gap exists because there is no study which focuses on the use of nanosilica in water-based muds in dynamic conditions. This research not only studies hole cleaning efficiency of water-based muds without and with nanosilica, but also studies the cuttings transport efficiency of degraded muds without and with nanosilica to bridge the gap in this area.

1.3 Objectives

This study embarks on the following objectives:

(1) To comparatively characterise the rheological properties, fluid flow behaviour and filtration properties of non-degraded and degraded water-based mud both with and without nanosilica.

(2) To study cuttings transportation efficiency of non-degraded and degraded water-based mud with and without nanosilica at various inclination holes (0° to 90°).

(3) To analyse cuttings transport efficiency of non-degraded and degraded water-based mud with and without optimum concentration of nanosilica in lifting different drill cuttings sizes with and without drill pipe rotations.

1.4 Hypotheses

The hypotheses of this research works are as follow:

(1) The presence of nanosilica in drilling fluids decreases shear stress *vs*. shear rate readings which could reduce the pump pressure required for mud circulation in drilling operations, especially when heavy mud is needed to drill deep formations to balance formation pressures.

(2) Well distribution of nanosilica particles in the mud disrupts excessive gel formation between gelling agents. This gel disruption reduces the attractive forces which is crucial for heavy muds and reduces progressive gels.

(3) Particle distribution of nanosilica in flowing mud increases cuttings transport efficiency. This is because as the mud flows in a turbulent state towards the surface, the presence of nanosilica in dispersed form which possesses high

surface area to volume ratio increases the interaction with drilled cuttings and enhances colloidal forces.

(4) Degraded mud affects cuttings lifting performance. Silica nanoparticles can improve drilled cuttings lifting performance in degraded mud because it reduces the degradation of rheological properties and thus improve lifting capacity of the mud as compared to mud without nanosilica.

(5) Drill pipe rotation plays an important role in cuttings transportation improvement for non-degraded and degraded water-based mud without and with nanosilica. However, after the optimum drill pipe rotation is reached, drill pipe rotation has no additional contribution to hole cleaning.

1.5 Scope of Study

The scope of study for this research works are:

(1) The experimental rig was modified to study the cuttings transport efficiency. Pipe ID (hole) of 2.75 inches and a pipe OD (drill pipe) of 1.05 inches were used as annular size. The scale of the experimental flow loop used in this research work was a scaled down representation of an actual hole drilled offshore Peninsular Malaysia (Ming *et al.*, 2014). The actual well was drilled using heavy mud (17.8 – 18.1 ppg) in an 8.5 inches hole, at a flow rate of about 380 gpm to reach over-pressurized zones in TA field. The experimental flow loop and the parameters used in this research was a scaled down replica of that well. The size of the well and the flow rate used were (annular size: 2.75 × 1.05 in, flow rate: 74 gpm). In this research, two different mud weights (9 and 12 ppg) were used for better understanding and comparison of cuttings transport efficiency to improve future predictions of different mud weights in cuttings transport performance. The test section used in this experimental work is 20 ft long. An experimental investigation of cuttings transport efficiency done by Ozbayoglu & Sorgun (2010) showed reasonable

accuracy of 10% from their empirical correlation and experimental data using a 12 ft annular test section. Thus, for this research work, a test section of 20 ft is used to gain higher accuracy of cuttings transport performance.

(2) Characterization of rheological properties of basic water-based mud and degraded water-based mud without and with nanosilica with concentrations from 0.5 to 1.5 ppb. Types of fluid flow behaviour were also covered.

(3) Performance study of basic water-based mud and degraded water-based mud in lifting drilled cuttings in different inclination holes (0° to 90°) without and with pipe rotation (0 to 180 rpm). The condition of the flow loop experiment was studied under turbulent flow regime (9 ppg mud: Re = 4047.1; 12 ppg mud: Re = 5136.7).

(4) Cuttings transportation efficiency was studied with various cuttings sizes that were irregular in shape ranged from 1.4 to 4.0 mm. These cuttings sizes were according to the range of sizes studied by Walker & Li (2000), Ramadan *et al.* (2004), and Duan *et al.* (2006).

(5) Water-based mud with and without nanosilica were degraded to 50℃, 80℃, and 120℃ in a jacketed heating tank before cuttings transportation efficiency was studied. This temperature range was chosen because the conventional water-based mud starts to degrade at 43℃ and completely fails at 120℃ (Amani *et al.*, 2012). A similar study was also conducted by Smith *et al.* (2018) where they investigated the performance of nano aluminium oxide and nanosilica in water-based mud at 50℃ and 80℃ in static condition.

1.6 Significance of Study

The significance of study for this research works are:

(1) This research can contribute an additional knowledge on cuttings transport in high temperature environments by studying the performance of nanosilica in degraded water-based mud. Cuttings transport efficiencies were studied in different inclination angles to simulate directional drilling. This research work complements previous works done by other researchers (Piroozian & Ismail, 2011; Abimbola *et al.*, 2014; Cai *et al.*, 2012; Yuan *et al.*, 2013; Yang *et al.*, 2015; Kang *et al.*, 2016) on drilled cuttings transport by presenting experimental results of non-degraded and degraded water-based mud with nanoparticles in wellbore cleaning.

(2) The oil and gas industry may utilize nonpolymeric additives such as nanoparticles (i.e. nanosilica) to improve the performance of water-based mud in high temperature wells. The findings from this research work improved cuttings transportation efficiency by 30.8 to 44% at room temperature and up to 15% at elevated temperatures which would increase the likelihood of successful extended drilling operations using nano-enhanced water-based mud.

(3) Nanosilica is a non-toxic additive and is highly available in Malaysia. Apart from being abundant, it is also able to increase the rheological properties of drilling mud under high temperatures.

1.7 Chapter Summary

Deeper holes are being drilled more frequently and high temperature holes are becoming a big problem because of the tendency of drilling mud to degrade thus affecting cuttings transport performance. There are numerous findings on the benefit of using nanomaterials in drilling mud for high temperature environments, however all these studies are conducted in static conditions. Literature on cuttings transportation of water-based mud with the presence of nanomaterials are still scarce in dynamic conditions.

This study investigates the effect of nanosilica in water-based mud in an experimental flow loop at various angles without and with pipe rotation. Cuttings transportation efficiency is also investigated after mud degradation. Nanosilica is introduced into water-based mud because of its thermal stability. This will mitigate mud degradation in high temperature holes and increase the rheological properties of the mud.

The experimental works were divided into three parts. All these parts were conducted using degraded water-based mud with and without silica nanoparticles. The first part was to study the rheological and fluid loss properties, the second part was to study the rheological behaviour of the mud, and the third part was to study the cuttings transportation efficiency in different hole inclinations and without and with different pipe rotations.

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