# ENHANCED CUTTINGS TRANSPORTATION IN DEVIATED AND HORIZONTAL WELLS USING POLYPROPYLENE–NANOSILICA COMPOSITE

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# DEDICATION

*This thesis is dedicated to Almighty God, the Prince of Peace, the King of Kings and the Giver of Life. It is also dedicated to my loving younger sister, Mrs. Ozioma Goodness Eforma, who sacrifice her hard-earned resources to ensure that I complete this thesis.*

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# ABSTRACT

Field cases revealed that cuttings transport optimization from the bit towards the surface eventuates in the cutback of drilling costs. In deviated and horizontal wells, cuttings transport is more complicated and has unremittingly been investigated due to complex fluid profile and the limitation of precise data on pipe rotation, hole angles, annular velocities, and cuttings sizes, which have to be considered concomitantly. Partially hydrolyzed polyacrylamide (PHPA), an extensively used polymer for cuttings transport due to its sterling drag-reducing feature, good viscosifying properties, and ease of solubility in water–based mud (WBM), has the problem of flocculation and viscosity at high temperature, which hinders the cuttings transport efficiency. Recently, polymer nanocomposite (PNC), a novel material formed from the hybrid of polymer and nanoparticle has received growing interest and is propounded for drilling operations because of its exceptional and intriguing properties. However, the behaviour of this material for drilling mud in a typical cuttings transport process is lacking in open literature. Herein, polypropylene–nanosilica composite (PP–$SiO_2$ NC) was synthesized by hot emulsion sol–gel method, and its surface charge was modified using (3–Aminopropyl) triethoxysilane. The modified (PP-$SiO_2$ NC-$NH_2$) and unmodified (PP–$SiO_2$ NC) were characterized by different investigative techniques to study their dispersion, micromorphology, bonding, and thermal stability. The PP–$SiO_2$ NC–$NH_2$ drilling muds were compared with those of the PHPA to investigate their effects on cuttings transport efficiency (CTE). The effect of annular velocities (between 66.1 and 234.1 ft/min), hole inclinations (from 45 to 90°), cuttings sizes (between 0.50 and 4.00 mm), and concentrations (between 0.4 and 1.2 g) of PP–$SiO_2$ NC–$NH_2$ and PHPA on CTE in a field–oriented cuttings transport flow loop with dimensions of 2.4–in.×1.2–in., 16–ft. long annulus were exclusively examined. Characterization data showed that amine layers were effectively deposited on the surface of the PP–$SiO_2$ NC–$NH_2$ particles and these particles were distributed between 80 and 390 nm, which signifies long term stability of drilling muds, especially at high temperature applications. All the mud samples of PP-$SiO_2$ NC-$NH_2$ were within the recommended operating limits, unlike 0.8 and 1.2 g of PHPA - their properties were greatly flocculated due to the PHPA's anionic character. The properties of WBM enhanced when PP-$SiO_2$ NC-$NH_2$ and PHPA were added, but higher CTEs occurred with the PP-$SiO_2$ NC-$NH_2$ drilling muds due to their uniform distribution and increased colloidal interactions with drilled cuttings. Concentrations of 1.2 g PP-$SiO_2$ NC-$NH_2$ and 0.4 g PHPA demonstrated the optimum concentrations for enhancement of rheological properties and were the most suitable choices for enhanced cuttings transport. With the highest annular velocity of 234.1 ft/min at the horizontal annulus (90°), the CTE of the WBM related to the largest cuttings size (2.80–4.00 mm) was enhanced from 82.4 to 96.2% by 1.2 g concentration of PP-$SiO_2$ NC-$NH_2$ with pipe rotation. Similarly, 0.4 g optimum PHPA concentration increased the CTE of the WBM from 82.4 to 94.6%. The transport of larger cuttings depends more on annular velocity, unlike that of the smaller cuttings, which was more influenced by mud viscosity. Furthermore, rotation of inner drill pipe and increase in annular velocity effectively increased the drag effects leading to higher cuttings transport. This study is advantageous for expanding the frontiers of knowledge in PNC application for drilling operations, especially for cuttings transport.

# ABSTRAK

Kajian kes menunjukkan bahawa pengoptimuman dalam pengangkutan rincisan dari bit gerudi ke permukaan boleh mengurangkan kos penggerudian. Bagi telaga yang melencong dan mendatar, pengangkutan rincisan adalah lebih rumit dan kurang dikaji secara mendalam berikutan profil cecair yang rumit dan data putaran paip gerudi, sudut lubang, halaju annulus, dan saiz rincisan yang terhad. Poliakrilamida terhidrolisis separa (PHPA) merupakan polimer yang digunakan secara meluas dalam pengangkutan rincisan berikutan kehebatan ciri pengurangan seretan dasar, sifat peningkatan kelikatan yang baik dan kebolehlarutan yang baik dalam lumpur dasar air (WBM). Walau bagaimanapun, bahan ini mempunyai masalah penggumpalan dan kelikatan pada suhu tinggi yang menjejaskan kecekapan pengangkutan rincisan. Kini, komposit nanopolimer (PNC), bahan novel yang terbentuk daripada hibrid polimer dan nanopartikel terus mendapat perhatian dan digalakkan penggunaannya dalam operasi penggerudian berikutan sifatnya yang menarik. Walau bagaimanapun, kesan bahan ini terhadap lumpur gerudi dalam proses pengangkutan rincisan adalah terhad perbahasannya. Dalam kajian ini, komposit polipropilena-nanosilika (PP–$SiO_2$ NC) disintesis menggunakan kaedah sol-gel emulsi panas dengan permukaannya diubah suai menggunakan (3-Aminopropil) trietoksisilan. Permukaan partikel terubah suai (PP-$SiO_2$ NC-$NH_2$) dan partikel tidak terubah suai (PP-$SiO_2$ NC) diciri menggunakan teknik penyelidikan yang berbeza bagi mengkaji penyerakan, morfologi mikro, ikatan, dan kestabilan haba. Lumpur gerudi PP-$SiO_2$ NC-$NH_2$ dibandingkan dengan PHPA bagi mengkaji kesannya terhadap kecekapan pengangkutan rincisan (CTE). Kesan halaju anulus (dari 66.1 hingga ke 234.1 kaki/min), kecondongan lubang (dari 45° hingga ke 90°), saiz rincisan (antara 0.50 dengan 4.00 mm), dan kepekatan PP-$SiO_2$ NC-$NH_2$ dan PHPA (antara 0.4 dengan 1.2 g) terhadap CTE telah dikaji menggunakan gelung aliran berdimensi 2.4 inci × 1.2 inci, 16 kaki panjang. Data pencirian menunjukkan bahawa lapisan amina telah terlekat secara berkesan pada permukaan partikel PP-$SiO_2$ NC-$NH_2$ yang bersaiz dari 80 hingga ke 390 nm, yang menandakan kestabilan jangka panjang lumpur gerudi, terutama pada pengaplikasian suhu tinggi. Semua sampel lumpur PP-$SiO_2$ NC-$NH_2$ berada pada had operasi yang disyorkan berbanding 0.8 g dan 1.2 g PHPA yang mudah tergumpal berikutan sifat anioniknya. Sifat-sifat WBM berjaya dipertingkat apabila PP-$SiO_2$ NC-$NH_2$ dan PHPA ditambah, tetapi CTE yang lebih tinggi berlaku dengan lumpur gerudi PP-$SiO_2$ NC-$NH_2$ berikutan taburannya yang seragam dan meningkatnya interaksi koloid dengan rincisan gerudi. Kepekatan 1.2 g PP-$SiO_2$ NC-$NH_2$ dan 0.4 g PHPA ialah kepekatan optimum bagi peningkatan sifat-sifat reologi dan pilihan paling sesuai untuk meningkatkan pengangkutan rincisan yang berkesan. Dengan halaju anulus tertinggi 234.1 min/kaki pada anulus mendatar (90°), CTE WBM bagi diameter rincisan terbesar (2.80–4.00 mm) meningkat dari 82.4 hingga ke 96.2% dengan dibantu kepekatan 1.2 g PP-$SiO_2$ NC-$NH_2$ dan putaran paip. Serupa juga, 0.4 g kepekatan optimum PHPA meningkatkan keupayaan pengangkutan WBM dari 82.4% ke 94.6%. Pengangkutan rincisan yang lebih besar bergantung pada halaju anulus berbanding rincisan lebih kecil yang dipengaruhi oleh kelikatan lumpur. Selain itu, putaran paip gerudi dan peningkatan halaju anulus telah meningkatkan kesan seret serta menghasilkan pengangkutan rincisan yang lebih tinggi. Kajian ini berfaedah dalam memperkasa pengetahuan tentang aplikasi PNC untuk operasi penggerudian, terutama terhadap pengangkutan rincisan.

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| 3D | - | Three dimensional |
| A–0.4 | - | Base mud + 0.4 g PP–$SiO_2$ NC–$NH_2$ |
| A–0.5 | - | Base mud + 0.5 g PP–$SiO_2$ NC–$NH_2$ |
| A–0.8 | - | Base mud + 0.8 g PP–$SiO_2$ NC–$NH_2$ |
| A–1.2 | - | Base mud + 1.2 g PP–$SiO_2$ NC–$NH_2$ |
| AM | - | Acrylamide |
| AMPS | - | Acrylamide methyl propane sulfonic acid |
| API | - | American petroleum institute |
| API FCT | - | Filter cake thickness under API conditions |
| API FL | - | Filtrate loss volume under API conditions |
| APTES | - | (3–Aminopropyl) triethoxysilane |
| ASTM | - | American standard test method |
| AV | - | Apparent viscosity |
| B–0.4 | - | Base mud + 0.4 g PHPA |
| B–0.5 | - | Base mud + 0.5 g PHPA |
| B–0.8 | - | Base mud + 0.8 g PHPA |
| B–1.2 | - | Base mud + 1.2 g PHPA |
| BM | - | Base mud |
| CF | - | Coefficient factor |
| CMC | - | Carboxyl methyl cellulose |
| CoF | - | Coefficient of friction |
| –$CONH_2$ | - | Amides group (ethanamide) |
| CTE | - | Cuttings transport efficiency |
| DLS | - | Dynamic light scattering |
| ECD | - | Equivalent circulating density |
| EDX | - | Energy dispersive x–ray analysis |
| EOR | - | Enhanced oil recovery |
| EP | - | Extreme pressure |
| ETF | - | Edge–to–face |
| EtOH | - | Ethanol |
| $Fe_2O_3$ NP | - | Ferric oxide nanoparticle |
| FESEM | - | Field emission scanning electron microscopy |

FTF - Face–to–face
FTIR - Fourier transform infrared spectroscopy
GBM - Gas–based mud
GS - Gel strength
HCl - Hydrochloric acid
HDPE - High density polyethylene
HLB - Hydrophilic–hydrophobic balance
HTHP - High pressure high temperature
HTHP FCT - Filter cake thickness under HTHP conditions
HTHP FL - Filtrate loss volume under HTHP conditions
IA - Itaconic acid
KCl - Potassium Chloride
LDPE - Low density polyethylene
MCNT - Multiwall carbon nanotubes
METU - Middle East Technical University
MTV - Minimum transport velocity
$Na_2CO_3$ - Soda ash
NaOH - Caustic soda
NH - Ammonia
$–NH_2$ - Amino group
$NH_4OH$ - Ammonium hydroxide
NPs - Nanoparticles
OBMs - Oil–based muds
–OH - Hydroxyl group
PAC - Polyanionic cellulose
PAC HV - High viscosity polynomic cellulose
PE - Polyethylene
PE–b–PEG - Polyethylene–block– (Polyethylene glycol)
PEG - Polyethylene glycol
P–HAR - Pipe to hole area ratio
PHPA - Partially hydrolyzed polyacrylamide
PNCs - Polymer nanocomposite
PP - Polypropylene
PP–$SiO_2$ NC - Unmodified polypropylene–nanosilica composite
PP–$SiO_2$ NC–$NH_2$ - APTES modified polypropylene–nanosilica composite
PSD - Particle size distribution

| | | |
|---|---|---|
| PV | - | Plastic viscosity |
| PVC | - | Polyvinyl chloride |
| ROP | - | Rate of penetration |
| Sand A | - | 0.50–0.99 mm |
| Sand B | - | 1.00–1.99 mm |
| Sand C | - | 2.00–2.79 mm |
| Sand D | - | 2.80–4.00 mm |
| $SiO_2$ | - | Silica nanoparticle/nanosilica |
| –SiOH | - | Silanol group |
| TEM | - | Transmission electron microscopy |
| TEOS | - | Tetraethyl orthosilicate |
| TGA | - | Thermal gravimetric analysis |
| $TiO_2$ | - | Titania/titanium dioxide |
| TUC | - | Technical University of Crete |
| TUDRP | - | Tulsa University Drilling Research Project |
| UTM | - | Universiti Teknologi Malaysia |
| WBMs | - | Water–based muds |
| XG | - | Xanthan gum |
| YP | - | Yield point |
| YP/PV | - | Transport capacity ratio |
| ZnO | - | Zinc oxide |
| $\zeta$–potential | - | Zeta potential |

# LIST OF SYMBOLS

$D_{hole}$ - Hole diameter

$D_{hyd}$ - Hydraulic diameter

$D_{pipe}$ - Pipe diameter

$F$ - Drag force

$N_{Re}$ - Reynolds number

$Q_m$ - Mud flow rate

$R$ - Particle diameter

$u$ - Average velocity

$VA_{mud}$ - Annular mud velocity

$V_{net}$ - Net rise velocity or upward velocity

$V_{slip}$ - Cuttings slip velocity

$\pi$ - Pi = 3.142

$\eta$ - Viscosity

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background of the Study

The rapid growth of industrialization and population has led to increasing global energy demand, while the primary energy sources, such as oil and natural gas are fast depleting (Li et al., 2018; Dhinesh and Annamalai, 2018; Vigneswaran et al., 2018; Nanthagopal et al., 2019). The petroleum industry is constantly searching for novel additives for drilling fluids and safer drilling practices that can drill in challenging wellbores. The essence for the novel additives in the challenging wellbores (deviated, highly deviated, horizontal, or extended reach wells) is to recover more hydrocarbons to meet the ever-growing global demand for energy. Nonetheless, drillings in these wells are met with one of the biggest challenges, which is the problems of poor cuttings transport (Boyou et al., 2019; Yeu et al., 2019).

During drilling, the velocity of the drilling mud must exert a sufficiently high force to overcome the effects of gravity. Normally, drilling mud contains enough mud velocity to carry out this function efficiently in vertical hole angles. In contrast, deviated and horizontal wells constitute more difficult problems. This is because circulation in these wells is proportional to the movement of cuttings in a stream bed. The cuttings follow a complex and tortuous path to the surface, in which some of them, especially the larger ones gravitate to the low side of the hole due to the hole inclination, as shown in Figure 1.1 (Epelle and Gerogiorgis, 2018). These make the cuttings not to travel too far before they reach the low side of the hole (Figure 1.1a).

According to Figure 1.1b, the larger cuttings and muds on the lower side have a lower rate of movement than the clean mud at the upper side. Due to increasing hole inclination, the cuttings travel downward and are forced to drop to the bottom of the hole due to a lack of lifting force in the flow (zero velocity at the wall). This problem can cause an increased coefficient of friction (CoF) of the drill string, pipe sticking or even loss of the entire well if not properly controlled. The problem is often aggravated due to the complex fluid circulation profile and limitation of precise oilfield data on wellbore parameters.

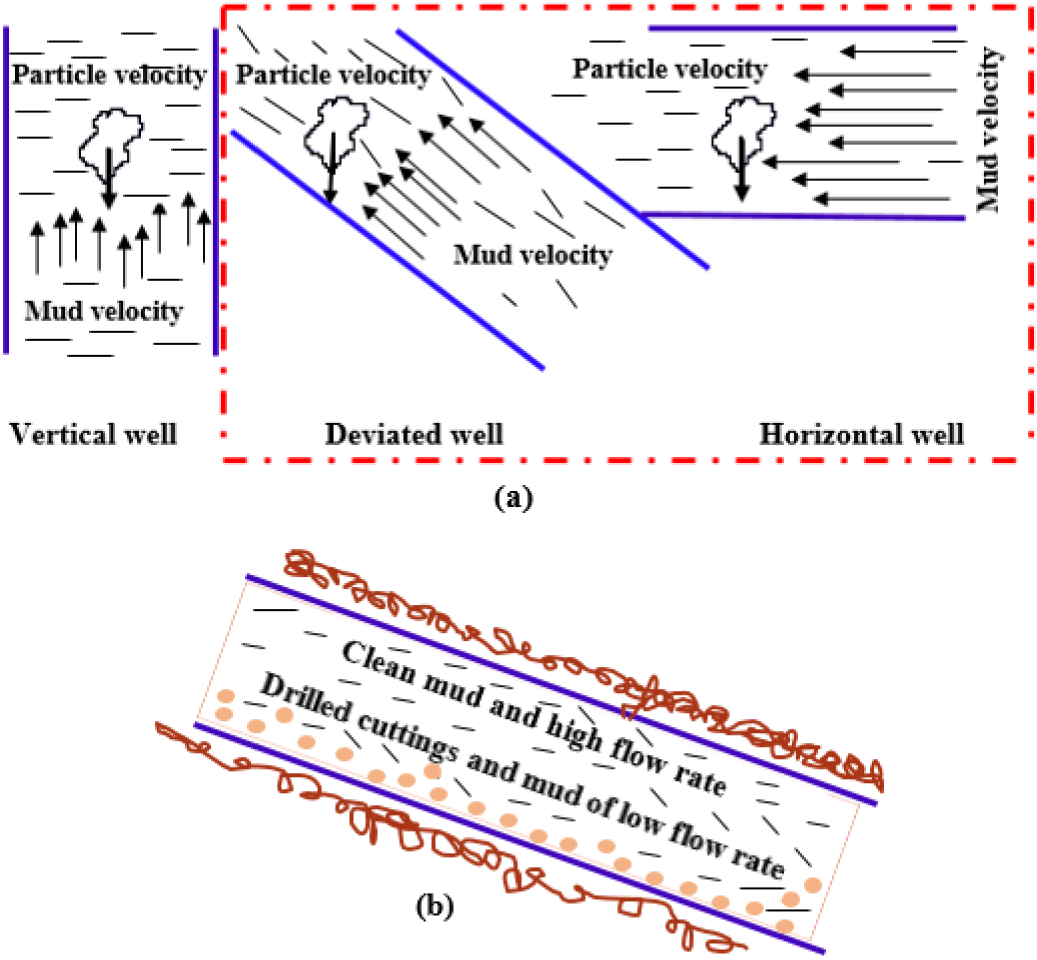

Figure 1.1 Particle movement: (a) In vertical and directional wells and (b) with mud (Epelle and Gerogiorgis, 2018).

Practically, it is impossible to remove all the cuttings by mere mud circulation, especially for deviated and horizontal wellbores. However, the efficiency can increase by providing enough annular velocity to the drilling mud and optimizing the drilling mud properties according to requirement (Samsuri and Hamzah, 2016; Egbue, 2017). Identifying the pump requirement to induce enough pressure that will produce high enough annular velocity is needed to support the continuous movement of cuttings towards the surface. Selecting optimal mud properties and introducing pipe movement by rotation will help in ensuring efficient cuttings transport by mechanically disturbing the cuttings bed (Egbue, 2017). These factors can help in preventing severe drilling problems that could have dramatically increase unproductive time and drilling costs.

Economic profits of drilling vertical wells are firmly established in field practice, but are not the case for drilling deviated, horizontal, or extended–reach wells due to more difficulty to reach the target pay zones of these wells (Ogbeide and Igbinere, 2016; Busahmin et al., 2017). However, the possible gain by increased production has renewed the interest of drilling operators in deviated and horizontal drillings. Efficient cuttings transport is one of the most important requirements for any successful drilling operation, most importantly drilling in deviated, horizontal wells, and extended–reach wells (Rooki et al., 2018; Boyou et al., 2019). Deviated wells are oil and gas wells whose inclination surpass 30° for most of their length and extended to highly deviated from 60° up to 89°. Horizontal wells are those wells which are drilled to an inclination of 90°, and maintains this inclination for a significant distance (Cayeux et al., 2016; Bizhani et al., 2016).

Drillings in deviated and horizontal wells developed offshore platforms through accessing impossible well locations, such as drilling into faults and obstructive areas that cannot be achieved in drilling vertical wells (Lyons et al., 2016; Egbue, 2017). Furthermore, the increase in horizontal displacement from a central platform is another advantage of drilling deviated or horizontal wells (Majid et al., 2018; Heshamudin et al., 2019). Increasing hole angle inclinations permit the increase in the drainage area and horizontal-reach wells (Cayeux et al., 2016; Bizhani et al., 2016). The longer horizontal-reach drilling can decrease the number of platforms needed to drill the reservoir in offshore locations (Cayeux et al., 2016). Another advantage of drillings in deviated and horizontal wells is the extended length of the completion zone through the reservoir (Cayeux et al., 2016; Bizhani et al., 2016). These acts allow the reservoir to contribute much more to the well's productivity. Nevertheless, the major technical challenge in drilling in these wells is linked to the gravitational effect as hole angle increases. When the hole angle rises, the axial component of the mud will decrease, while the lateral component will increase (Saxena et al., 2017; Katende et al., 2019). The success of drilling in these wells depends on the circulated drilling muds used to remove cuttings from the drilling hole.

Drilling fluids are an indispensable component of the oil and gas industry. Primarily, these fluids are used to control the formation pore pressure and transport drilled cuttings to the surface (Samsuri and Hamzah, 2016). The process of transporting drilled cuttings from the hole towards the surface is known as the cuttings transport. Based on different experimental data in the literature, several parameters influence cuttings transport in drilled wells. The influence of these parameters is usually more complicated when drilling deviated and horizontal wells than drilling vertical wells (Adari et al., 2000; Bilgesu et al., 2007). Bilgesu et al. (2007) classified these parameters into three categories: operational parameters, cuttings related characteristics, and drilling mud parameters.

Operational factors that influence cuttings transport are the mud velocity or flow rate, the drill pipe rotary speed, rate of penetration (ROP), pipe eccentricity, and hole angle inclination. Irrefutably, the flow rate has a significant positive effect among all these parameters and the transport capacity of drilling muds is greatly affected by the fluid velocity profile in the annulus (Ismail et al., 2016; Amanna et al., 2016). The reduction in the mud velocity at the low side of the hole has been described in numerous investigations as the main cause of poor cuttings transport for deviated and horizontal wellbores (Heshamudin et al., 2019; Yeu et al., 2019). Increased mud velocity has the benefit of decreasing the cuttings bed height, but can also cause an increase in annular pressure drop. This will in turn increase equivalent circulating density (ECD) (Naderi and Kahmechi, 2018; Rooki et al., 2018). Therefore, optimized mud velocity should be used to prevent hole stability problems.

Laboratory and field results showed that drill pipe rotation has minimum to a significant influence in enhancing the cuttings transport process (Heydari et al., 2017; Moraveji et al., 2017). The degree of the enhancement is a combined influence of drill pipe rotation speed, mud rheological properties, flow rate, cuttings size, and the dynamic characteristic of drill bit (Sayindla, 2018; Heshamudin et al., 2019). Hole angle inclination has a pronounced influence on cuttings transport (Saxena et al., 2017; Moraveji et al., 2017). For a low hole angle inclination below 10°, the cuttings lifting process is the same as that of the vertical annulus (Egenti, 2014). For deviated wells between the critical angle of 40° and 60°, there is a significant reduction in the cuttings lifting process. The reduction is due to the decrease in the vertical component of mud velocity and higher influence of gravitation force on drilled cuttings (Rooki et al., 2018; Heshamudin et al., 2019).

Cuttings size, density, and shape factor are significant cuttings related parameters. These parameters impact the flow dynamics of cuttings in a flowing mud; nonetheless, there is little control over these parameters because of their dependence on the type of bit used and other drilling conditions (Bilgesu et al., 2007). They are considered significant in cuttings transport process because interfacial stress hinge on the cuttings size and cuttings shape has effects on the sagging of cuttings (Ernesto et al., 2016; Werner et al., 2017).

Mud parameters that influence the lifting of rock cuttings are density and rheological properties. The density of the drilling fluid should be such that it provides a hydrostatic head greater than the formation pressure to prevent any kind of invasion of formation fluids inside the well (Fattah and Lashin, 2016). The weighing agents require a higher yield point and viscosity so that the cuttings transport process is not affected by the sagging of these agents (Fattah and Lashin, 2016). The rheological characteristics are often enhanced and controlled to make drilling mud to function effectively, and also to minimize drilling cost. Mud viscosity is used to impact the flowability and suspension of weighting materials (Rooki et al., 2018; Pang et al., 2019).

A viscous mud is often the practiced solution in the oil and gas industry. Mud thinners often come into play, to reduce the magnitude of viscosity and yield point if they are too high (Ismail et al., 2019). The determination of the mud’s transport capacity becomes more difficult with all these mentioned parameters acting concomitantly. Therefore, optimum mud properties are needed for efficient lifting of cuttings and suspension. Inability to manage these parameters effectively often leads to unwanted drilling problems, such as poor cement jobs, lost circulation, stuck pipe, faster bit wear, high torque and drag, decrease in ROP, etc. (Kamyab and Rasouli, 2016; Caenn et al., 2017; Hakim et al., 2018). The severity of these problems rests on the amount and position of the cuttings distributed along the borehole (Kamyab and Rasouli, 2016).

In recent years, water–based muds (WBMs) and oil–based muds (OBMs) have been broadly used to drill petroleum reservoirs, but due to the lower ecological impact and operating cost, WBMs are the most desired (Assembayev et al., 2015; Fattah and Lashin, 2016; Sayindla et al., 2017). Nevertheless, the properties of WBM needs additional manipulations for enhanced cuttings lifting due to their degradation with increasing drilling depth. Therefore, cuttings lifting by conventional WBM can be easier if suitable additive like nanoparticles (NPs) is added in the preparation. Some studies conducted showed that NPs drilling fluids have the tendency of increasing the drag and lift forces acting on drilled cuttings. They also enhanced the heat transfer characteristics of WBM, improved the binding ability of cuttings, and increased the gel formation (Samsuri and Hamzah, 2016; Gbadamosi et al., 2018a, b; Boyou et al., 2019). However, the efficacy of applying NPs drilling fluids is limited at deeper drilling depths due to the ease at which they aggregate and agglomerates, that directly reduced their dispersion, physical stability, and efficiency (Mahmoud et al., 2016; Elochukwu et al., 2017; Fakoya and Shah, 2017).

More recently, it has been found that the properties of WBMs containing hybrids of polymers and NPs to form polymer nanocomposites (PNCs) are enhanced. This is because of the synergistic effects between polymers and NPs, and efficient dispersion of NPs within the polymer matrix (Mao et al., 2015; Jain et al., 2016; Xu et al., 2018; Mohamadian et al., 2019). The formation of relatively high average specific surface areas and the micro–nanosized particles of the PNCs also contribute to the increased performance of drilling muds (Mao et al., 2015). PNCs additives are used to modify the rheology and control the filtration properties of drilling fluids (Jain and Mahto, 2015). They are also used as lubricants, clay swelling inhibitors, and thermal stabilizers in WBMs (Mao et al., 2015; Jain et al., 2016; Xu et al., 2018; Abdollahi et al., 2018; Mohamadian et al., 2019; Davoodi et al., 2019). Thus, the synergistic effect between polymers and NPs has helped to improve the properties of conventional drilling fluids.

Synthetic polypropylene (PP) has recently captured the attention of investigators for drilling fluids. This is because of its easy availability, low cost, high chemical, and temperature–resistance, self–assembly, viscoelastic properties, and low density (Ismail et al., 2016; Hakim et al., 2018; Yeu et al., 2019; Heshamudin et al., 2019). Among all the NPs, silica nanoparticles or nanosilica ($SiO_2$ NPs) research is the most investigated. This is due to their high thermal stability, exceptionally strong bond network, good adhesion property at the interface, less toxicity, small enough size, and high specific surface area-to-volume ratio (Elochukwu et al., 2017; Gbadamosi et al., 2018a, b; Boyou et al., 2019; Kok and Bal, 2019). From the review of several experimental findings, WBMs formulated with a hybrid of $SiO_2$ NPs and polymers have shown enhanced properties performance. This is because of their fine dispersibility and less-viscous character (Elochukwu et al., 2017; Kok and Bal, 2019; Abdollahi et al., 2018; Davoodi et al., 2019).

The efficient impact of $SiO_2$ NPs with polymers in enhancing the characteristics of WBMs often results from an increase in surface area-to-volume ratio of the composites. This act increases the interaction in the colloidal systems and the interaction sites with polymers. Furthermore, $SiO_2$ NPs can act as receptors for polymers, which allow functionalization and coating over it to reduce their agglomerates and increase their dispersion (Mao et al., 2015; Kok and Bal, 2019). The dispersion and stability of $SiO_2$ NPs in combination with polymers are increased when a suitable surfactant is used to modify the surface of formed PNC bearing $SiO_2$ NPs (Cao et al., 2017). Therefore, to increase the dispersion and stability of PNC material containing $SiO_2$ NP, it is necessary to improve the interfacial adhesion properties between the polymer and $SiO_2$ NP by method of surface charge modification (Elochukwu et al., 2017; Cao et al., 2017). modifying their surface with a suitable surfactant that can neutralize the negative hydroxyl ions of the $SiO_2$ NPs. This behaviour might cause stability among $SiO_2$ NPs, which can increase the performance of the composite in a conventional WBM.

## 1.2 Problem Statement

The application of efficient additives in the field to optimize cuttings transport from the bit towards the surface has resulted in the cutback of drilling costs and an increase in oil production. In deviated and horizontal wells, the lifting of cuttings has been a challenging phenomenon in the oil and gas industry for a long period and has unremittingly been investigated. Given the complexity of different cuttings sizes, complex fluid flow profile, and limitation of precise drilling data that have to be considered concomitantly in the cuttings transport process, drilled cuttings have a higher tendency to gravitate to the low side of the hole at these inclinations. This can result in severe wellbore problems, such as hole collapse, pipe sticking issue, lost circulation, bit wear, formation damage, etc. (Samsuri and Hamzah, 2016; Gbadamosi et al., 2018a, b; Boyou et al., 2019).

Today, among the numerous polymeric additives that have been applied to improve the efficiency of conventional WBMs for cuttings transport, only the PHPA has recorded a few successes when evaluated under different field conditions. This is due to its viscosity-enhancing effect and ease of solubility in WBMs (Kadaster et al., 1992; Hale and Mody, 1993; Lam et al., 2015). However, the application of the WBM system containing PHPA is limited at extreme downhole conditions of high-temperature high-pressure (HTHP). At these conditions, the long-chain molecules and bonds of PHPA are broken, which affects the stability and rheological properties of the WBM system (Hale and Mody, 1993; Lam et al., 2015). Also, the mud loses its shear-thinning property under the static and dynamic aging conditions and causes excessive gel strength, yield point, and viscosity. These events often result in undue mud's flocculation, which hinders the cuttings transport efficiency and allows the mud to seep easily into the drilled formation (Hale and Mody, 1993; Lam et al., 2015). Besides, WBMs formulated with PHPA has led to fast accumulation of drilled cuttings in the flowing mud stream which resulted in the thickening of the mud, reduced pumpability, increased ECD, and higher than expected drilling costs (Hale and Mody, 1993; Lam et al., 2015). These issues observed in the field application of PHPA mud systems are great concerns to drilling operators.

Therefore, to address this issue, a well-dispersed and less-viscous WBM system containing composited $SiO_2$ NP with PP (PP-$SiO_2$ NC) could be applied to enhance the poor temperature resistance of the conventional WBM containing PHPA. Nevertheless, the WBM system formulated with unmodified $SiO_2$ NP or unmodified $SiO_2$ NP with polymers can form agglomerates and becomes unstable. These phenomena are due to the adhesion of the particles to each other by weak forces leading to the formation of sub-micron sized particles. This has resulted in the reduction of the mud's performance and unsuccessful drilling operations (Elochukwu et al., 2017; Mahmoud et al., 2017). To solve this problem, there is the need to make the zeta potential (ζ–potential) magnitude of the composite of PP and $SiO_2$ NP to become highly positive within the stable region, which will improve the dispersibility and stability of the composite. This improvement can be achieved by the modification of the surface charge of the composite to efficiently exploit its full potentials for an improved cuttings transport and efficient drilling process. One such effective method of modification is by attaching a silane coupling agent, such as (3-Aminopropyl) triethoxysilane (APTES) to the surface of the PP-$SiO_2$ NC particles to enhance their dispersion and stability in the WBM system (Omurlu et al., 2016; Cao et al., 2017). Therefore, the attachment of APTES to the surface of the PP-$SiO_2$ NC was seen as positive for the improvement in the properties of conventional WBM system. Thus, such modification was considered in this research to prevent any possible agglomeration of the nanocomposite and make it more stable in the WBM system.

Therefore, the questions to be answered in this research are:

i. In what way can the magnitude of ζ–potential of modified PP–$SiO_2$ NC particles influence the properties of WBM for increased cuttings transport?
ii. How will the concentrations of modified PP–$SiO_2$ NC compare with those of conventional PHPA in enhancing the rheological and filtration control properties of basic WBM?
iii. How will different drilling parameters, such as hole angle inclinations, cuttings diameter, annular mud velocities, and concentrations of modified PP–$SiO_2$ NC and PHPA used in WBMs interact to influence the cuttings transport process in deviated and horizontal wellbores?

## 1.3 Objectives of the Study

The overall aim of this research is to acquire an understanding of the influence of APTES modified PP–$SiO_2$ NC on the performance of basic WBM for the cuttings transport process. This aim was achieved through the following objectives:

i. To synthesize PP and $SiO_2$ NP through hot emulsion sol–gel process to form a PP–$SiO_2$ NC and modify the synthesized PP–$SiO_2$ NC by using aminosilane molecules (APTES).
ii. To characterize the synthesized PP–$SiO_2$ NC and determine its ζ–potential as well as its physical properties, such as size distribution, chemical compounds, bonding, surface, micromorphology, and thermal stability.
iii. To compare the rheological, bit lubricating, and filtration properties of the basic WBM with modified nanocomposite and oilfield PHPA under static test conditions.
iv. To determine the performance of the modified PP–$SiO_2$ NC and PHPA on a field–oriented cuttings transport flow loop with various drilling parameters towards cuttings transport efficiency.

## 1.4 Scope of the Study

Based on the objectives enumerated, the scope of this research is as follows:

i. Synthesizing the PP–$SiO_2$ NC particles using hot–emulsion sol gel process in the presence of nonionic surfactant.
ii. Modifying the surfaces of the synthesized PP–$SiO_2$ NC particles using APTES in the presence of caustic soda.
iii. Characterizing the synthesized PP–$SiO_2$ NC particles with or without modification by aminosilane molecules (APTES).
iv. Formulating and performing mud properties tests at 78 °F (before thermal aging tests) and 300 °F (after thermal aging tests) for 16 hours in a 4–roller

oven. Four different concentrations between 0.4 and 1.2 g of each of the modified PP–$SiO_2$ NC and PHPA were tested and evaluated.

v. Designing a field–oriented cuttings transport flow loop with dimensions: 16–ft. long transparent acrylic–pipe annular test section with an internal diameter of the outer pipe 2.4 in. A polyvinyl chloride (PVC) pipe about 16–ft. with an outer pipe diameter of 1.2 in. with both ends closed to prevent fluid exits and the inner drill pipe was located inside the 16–ft. acrylic–pipe to maintain a concentric annulus (i.e. 0% eccentricity).

vi. Sieving various sizes of sandstone grains as test cuttings into four different diameters in the range of 0.50 – 0.99 mm, 1.00 – 1.99 mm, 2.00 – 2.79 mm, and 2.80 – 4.00 mm.

vii. Identifying the various drilling parameters used in the cuttings transport process. Annular mud velocity in the range between 66.1 and 234.1 ft/min, hole–angle range between 90° and 45° from the vertical, and a static drill pipe and drill pipe rotation speed of 150 rpm were used.

## 1.5 Significance and Original Contribution of this Study

To ensure a secure energy future, new systems and processes are being developed through research and development to overcome the shortcomings of the well–known conventional WBM. One of such systems is the application of PNC to enhance the properties of drilling fluids. New developments in basic WBM for drilling oil and gas wells encompass the addition of PNCs to improve the rheological, lubricity, and filtration control properties of the process for drilling operations. This study makes a comparative analysis of basic WBM, basic WBM with PNC, and basic WBM with PHPA. The study seeks to understand their performance at the dynamic scale-in typical wellbore drilling conditions. The significance of this research is to extend the frontier of knowledge in the cuttings transport process through the understanding of the flow dynamics of PNC application in cuttings transport. This study is advantageous for enhancing the recovery of drilled cuttings at the surface and will prove important in contributing to the ever–increasing energy demand. Also, the drilling operations will become more efficient with improvement in the transport of drilled cuttings with modified PP–$SiO_2$ NC additive. This can surely translate to cost saving to drilling operators. Furthermore, the modified PP–$SiO_2$ NC product can be applied in other areas of the oil and gas industry, such as enhanced oil recovery (EOR), workover operation, coating jobs, reservoir characterization, and completion jobs.

## 1.6 Thesis Structure and Organization

Chapter 1 contains a brief overview and background of cuttings transport in deviated and horizontal wells. It explains the aim and objectives of the research, the research problems, the scopes, gaps in the existing knowledge of the area of research and the significance of the research.

Chapter 2 outlined a detailed review of previous works related to the theme of the research. It explains the drilling fluid architecture. It describes the concept of the cuttings transport process and discusses the various drilling parameters affecting it. It presents the shortcomings of PHPA drilling muds and the synergic application of polymers with particles in the nanometer domain to overcome these shortcomings. Finally, it presents the applications of nanocomposites as additives for drilling fluid.

Chapter 3 presents a detailed procedure for the preparation, modification and characterization of PP–$SiO_2$ NC drilling muds. Moreover, the materials, apparatus, equipment, and step–by–step guide for achieving the procedures of experiments as related to each objective are explained in detail.

Chapter 4 discusses the results and outcomes of nanocomposites characterization. It also outlined the performance and comparative analysis of the modified nanocomposite and PHPA under static test conditions and in a field–oriented cuttings transport flow loop.

Chapter 5 concludes the thesis with a summary of the main outcomes of the research and recommendations for future works.

## 1.7 Chapter Summary

This chapter discusses the importance of transporting drilled cuttings from the wellbore to the surface and the challenges often encountered while carrying out this task. It presents why cuttings lifting out of the annular environment is more problematic in drilling the deviated and horizontal wells than the vertical wells. Also, it discusses the limitation of WBM system formulated with polymers and expounds why hybrid of polymers and nanoscale agent are used to improve the properties of the WBM system. It highlights the aim and objectives of this thesis, which is to determine and compare the effect of the modified PP–$SiO_2$ NC and PHPA in improving cuttings transport efficiency. To achieve the research objectives, the scope and the significance of the study were clearly stated. Also, it presents the benefits and expected contribution of this research to the oil and gas industry. Finally, the structure of the thesis from the introductory section to conclusions is presented.

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# APPENDIX A

# LIST OF PUBLICATIONS

The thesis contains the following research articles published during the course of this research.

## Journal with Impact Factor

1. **Oseh, J.O**., Mohd Norddin, M.N.A., Muhamad., H.N., Ismail, I., Gbadamosi, A.O., Agi, A. and Ismail, A.R., Blkoor, S.O. (2020) Influence of (3–Aminopropyl) triethoxysilane on entrapped polypropylene at nanosilica composite for shale swelling and hydration inhibition, Journal of Petroleum Science and Engineering, 194, (107560), 1-16. doi: 10.1016/j.petrol.2020.107560 (**Q1, IF: 3.706**).
2. **Oseh, J.O**., Mohd Norddin, M.N.A., Ismail, I., Gbadamosi, A.O., Agi, A. and Ismail, A.R. (2020) Experimental investigation of cuttings transportation in deviated and horizontal wellbores using polypropylene–nanosilica composite drilling mud, *Journal of Petroleum Science and Engineering*, 189, (106958), 1–24. 10.1016/j.petrol.2020.106958. (**Q1, IF: 3.706**)
3. **Oseh, J.O**., Mohd Norddin, M.N.A., Ismail, I., Ismail, A.R., Gbadamosi, A.O. and Agi, A. (2019) Effect of the surface charge of entrapped polypropylene at nanosilica–composite on cuttings transport capacity of water-based muds, *Applied Nanoscience*, 10(1), 61–82. (**Q2, IF: 2.880**)
4. **Oseh, J.O**., Mohd Norddin, M.N.A., Ismail, I., Gbadamosi, A.O., Agi, A. and Mohammed, H.N. (2019) A novel approach to enhance rheological and filtration properties of water–based mud using polypropylene–silica nanocomposite, *Journal of Petroleum Science and Engineering,* 181, (106264), 1–25. https://doi.org/10.1016/j.petrol.2019.106264. (**Q1, IF: 3.706**)
5. Oseh, J.O., Norddin, M.N.A.M., Ismail, I., Gbadamosi, A.O., Agi, A., Ismail, A.R., Manoger, P., Ravichandran, K. (2020) Enhanced cuttings transport efficiency of water-based muds using (3–Aminopropyl) triethoxysilane on

polypropylene-nanosilica composite, *Arabian Journal of Chemistry*. pp. 1-17. pp. 1-17. https://doi.org/10.1016/j.arabjc.2020.07.004. (**Q2, IF: 4.762**)

6. **Oseh, J.O**., Mohd Norddin, M.N.A., Ismail, I., Gbadamosi, A.O., Agi, A. and Ismail, A.R. (2019) Study of cuttings lifting with different annular velocities using partially hydrolyzed polyacrylamide and enriched polypropylene–nanosilica composite in deviated and horizontal wells, *Applied Nanoscience*, 10(3), 971–993. (**Q2, IF: 2.880**).

## Additional Publications

The following are additional publications obtained during the period of this research.

## Journal with Impact Factor

1. **Oseh, J.O**., Mohd Norddin, M.N.A., Ismail, I., Ismail, A.R., Gbadamosi, A.O., Agi, A., Ogiriki, S.O. (2019) Investigating almond seed oil as potential biodiesel-based drilling mud, *Journal of Petroleum Science and Engineering,* 181, (106201). 1–16. 10.1016/j.petrol.2019.106201. **(Q1, IF: 3.706**)
2. **Oseh, J.O**., Mohd Norddin, M.N.A., Farooqi, F., Ismail, A.R., Ismail, I., Gbadamosi, A.O., Agi, A. (2019) Experimental investigation of the effect of henna leaf extracts on cuttings transportation in highly deviated and horizontal wells, *J. Petrol. Explor. Prod. Technol*., 9(3), 2387–2404. (**Q3, IF: 1.100**)

## Indexed Journal

1. **Oseh, J.O**., Mohd Norddin, M.N.A., Sidiqi, A.R., 2019. Improving the Lifting Capacity of Drilled Cuttings Using Henna Leaf Extracts and Lignite in Bentonite Water-Based Drilling Mud, *Journal of Engineering and Technological Sciences,* 51(3), 355–368. (**Indexed by Scopus**)

## Indexed Conference Proceedings

1. **Oseh, J.O**., Mohd Norddin, M.N.A., Ismail, I., Ismail, A.R., Gbadamosi, A.O., Agi, A., Ogiriki, S.O. (2019) Performance Evaluation of a Benign Oil-Based Mud from Non-Edible Sweet Almond Seed '*prunus amygdalus dulcis'* Oil. *In: SPE-198717-MS. Nigeria Annual International Conference and Exhibition*, 5–7 August, Lagos, Nigeria, 1–25. (**Indexed by Scopus**)