EFFECT OF NANOPARTICLES IN CUTTINGS TRANSPORT PERFORMANCE OF WATER BASED MUDS AT ECCENTRIC DRILL PIPE

RAFEQ ALI HUSSEIN ABUHOUREYAH

UNIVERSITI TEKNOLOGI MALAYSIA

EFFECT OF NANOPARTICLES IN CUTTINGS TRANSPORT PERFORMANCE OF WATER BASED MUDS AT ECCENTRIC DRILL PIPE

RAFEQ ALI HUSSEIN ABUHOUREYAH

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Faculty of Chemical and Energy Engineering

Universiti Teknologi Malaysia

FEBRUARY 2023

ACKNOWLEDGEMENT

In preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my main thesis supervisor, Dr. Mohd Nooral Anam Norddin, for encouragement, guidance, critics and friendship. I am very thankful for his guidance, advices and motivation. Without his continued support and interest, this thesis would not have been the same as presented here. My fellow postgraduate student should also be recognised for their support. My sincere appreciation to my family members specially to my father who passed away while I doing this project also to my brother Abullah who always support me and guid me since my early stages. also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space.

ABSTRACT

One of the major issues for drilling operations is achieving effective cuttings transport, particularly in extended-reach drillings (ERD) with horizontal and highly deviated sections. The main objective of the present study is to investigate and compare the application of different nanoparticles (NPs), such as nanosilica (SiO_2), aluminium oxide (Al_2O_3), magnesium oxide (MgO), and copper oxide (CuO) for improvement in cuttings transport in a full wellbore section at both eccentric and concentric drill pipes. Water-based mud (WBM) was mixed with 0.13 and 0.26 wt.% of each of the NPs to create NP drilling fluids, which were then tested for rheological and filtration characteristics. The flow loop is 20 feet long, 2.4 inches wide (2.4-in. ID), and 1.4 inches thick (1.4-in OD). By circulating the tested fluid samples into the test section vertically to horizontally while controlling the flow rates (1.9, 2.15, 2.4 L/s), cuttings sizes (1.10–1.4 mm; 1.5–1.7 mm; 1.8–2.0 mm), hole angles (0, 30, 60, and 90^{o}), and drill pipe eccentricity (e = 0; e = 1.0), the cuttings transport experiments were carried out. Simulating actual field circumstances is the aim of such a change in the operating parameters. The parameter used to assess hole cleaning is known as the "cuttings transport ratio (CTR)," which is calculated as the weight of recovered cuttings divided by the weight of injected cuttings. According to the findings, conventional WBMs' rheological properties are successfully improved by NPs, which improves borehole cleaning and drilled cutting suspension. With a higher NP concentration, the WBM's filtration capabilities were enhanced. The ideal concentration of NPs for rheological characteristics is 0.13 wt.%, whereas the ideal concentration for filtration control properties is 0.26 wt.%. In contrast, MgO yielded the lowest CTR, followed by SiO_2, Al_2O_3, and drilling muds containing CuO mud samples produced the highest CTR. Their unique morphologies and various interactions with bentonite in the fluid system were linked to these variations in CTR. The cuttings are best transported at 0°, then 30°, next 90°, with 60° being the least-cleaning hole angle. Cutting behaviour is heavily influenced by the slope and geometry of the hole. At various flow rates, the concentric annulus provided a greater CTR than the eccentric drill pipe. However, flowrate is a major factor in eccentricity, and flow rates greater than 2.4 L/s may result in higher CTE pipe eccentricity. This research is the first effort to assess the use of various NP additions to improve the capacity of drilling fluids to circulate and move drilled cuttings out of the wellbore. With the help of NPs, the cuttings transport performance of WBM can be reasonably improved, and the project risks may thus be reduced. Thus, the study is expected to open new directions in developing NPs material as potential cuttings transport agents.

ABSTRAK

Salah satu isu utama untuk operasi penggerudian ialah mencapai pengangkutan keratan yang berkesan, terutamanya dalam penggerudian jangkauan lanjutan (ERD) dengan bahagian mendatar dan sangat menyimpang. Objektif utama kajian ini adalah untuk menyiasat dan membandingkan penggunaan zarah nano (NPs) yang berbeza, seperti nanosilika (SiO2), aluminium oksida (Al2O3), magnesium oksida (MgO), dan kuprum oksida (CuO) untuk penambahbaikan dalam keratan. mengangkut dalam bahagian telaga penuh di kedua-dua paip gerudi sipi dan sepusat. Lumpur berasaskan air (WBM) dicampur dengan 0.13 dan 0.26 wt.% setiap NP untuk mencipta cecair penggerudian NP, yang kemudiannya diuji untuk ciri reologi dan penapisan. Gelung aliran adalah 20 kaki panjang, 2.4 inci lebar (2.4 inci ID) dan 1.4 inci tebal (1.4 inci OD). Dengan mengedarkan sampel bendalir yang diuji ke dalam bahagian ujian secara menegak ke mendatar sambil mengawal kadar aliran (1.9, 2.15, 2.4 L/s), saiz keratan (1.10–1.4 mm; 1.5–1.7 mm; 1.8–2.0 mm), sudut lubang (0, 30, 60, dan 90o), dan kesipian paip gerudi (e = 0; e = 1.0),eksperimen pengangkutan keratan telah dijalankan. Mensimulasikan keadaan medan sebenar adalah matlamat perubahan sedemikian dalam parameter operasi. Parameter yang digunakan untuk menilai pembersihan lubang dikenali sebagai "nisbah pengangkutan keratan (CTR)," yang dikira sebagai berat keratan pulih dibahagikan dengan berat keratan yang disuntik. Menurut penemuan, sifat reologi WBM konvensional berjaya diperbaiki oleh NP, yang menambah baik pembersihan lubang gerudi dan penggantungan pemotongan gerudi. Dengan kepekatan NP yang lebih tinggi, keupayaan penapisan WBM telah dipertingkatkan. Kepekatan ideal NP untuk ciri reologi ialah 0.13 wt.%, manakala kepekatan ideal untuk sifat kawalan penapisan ialah 0.26 wt.%. Sebaliknya, MgO menghasilkan CTR terendah, diikuti oleh SiO2, Al2O3, dan lumpur penggerudian yang mengandungi sampel lumpur CuO menghasilkan CTR tertinggi. Morfologi unik mereka dan pelbagai interaksi dengan bentonit dalam sistem bendalir dikaitkan dengan variasi dalam CTR ini. Keratan paling baik diangkut pada 0°, kemudian 30°, 90° seterusnya, dengan 60° ialah sudut lubang paling kurang pembersihan. Tingkah laku pemotongan banyak dipengaruhi oleh cerun dan geometri lubang. Pada pelbagai kadar aliran, anulus sepusat memberikan CTR yang lebih besar daripada paip gerudi eksentrik. Walau bagaimanapun, kadar alir adalah faktor utama dalam kesipian, dan kadar aliran lebih daripada 2.4 L/s boleh mengakibatkan kesipian paip CTE yang lebih tinggi. Penyelidikan ini merupakan usaha pertama untuk menilai penggunaan pelbagai tambahan NP untuk meningkatkan kapasiti cecair penggerudian untuk mengedar dan memindahkan keratan gerudi keluar dari lubang telaga. Dengan bantuan NP, prestasi pengangkutan keratan WBM boleh dipertingkatkan dengan munasabah, dan risiko projek boleh dikurangkan. Justeru, kajian ini dijangka membuka hala tuju baharu dalam membangunkan bahan NP sebagai agen pengangkutan keratan yang berpotensi.

TABLE OF CONTENTS

	TITLE	PAGE
	DECLARATION	**iii**
	DEDICATION	**iv**
	ACKNOWLEDGEMENT	**v**
	ABSTRACT	**vi**
	ABSTRAK	**vii**
	TABLE OF CONTENTS	**viii**
	LIST OF TABLES	**xiii**
	LIST OF FIGURES	**xiv**
	LIST OF ABBREVIATIONS	**xviii**
	LIST OF SYMBOLS	**xix**
CHAPTER 1	**INTRODUCTION**	**1**
1.1	Background of the Study	1
1.2	Problem Statement	6
1.3	Research Questions	7
1.4	Research Objectives	8
1.5	Scope of the Study	8
1.6	Significant of the Study and Contribution to Knowledge	9
CHAPTER 2	**LITERATURE REVIEW**	**11**
2.1	Water-Based Muds	11
2.2	Properties of Water-Based Muds	13
	2.2.1 Density	13
	2.2.2 Plastic Viscosity	13
	2.2.3 Apparent Viscosity	15
	2.2.4 Yield Point	15
	2.2.5 Gel Strength	17

2.2.6 pH 18

2.3 Rheological Model of Drilling Fluid (Fluid Flow Behaviour) 18

2.3.1 Bingham Plastic Model 19

2.3.2 Power Law Model 20

2.3.3 Herschel-Bulkley (Modified Power Law) Model 21

2.3.4 Casson Model 22

2.3.5 Robertson-Stiff Model 22

2.4 Cuttings Transport Mechanism 23

2.4.1 Force Analysis 23

2.4.1.1 The Gravitational Force, Fg 24

2.4.1.2 The Frictional Force, Ff 24

2.4.1.3 The Lift Force, FL 25

2.4.1.4 The Drag Force, FD 26

2.4.1.5 The Buoyancy Force, Fb 26

2.4.2 Flow Pattern of Cuttings Transportation 27

2.4.2.1 Homogeneous Suspension 28

2.4.2.2 Heterogeneous Suspension 28

2.4.2.3 Suspension/Saltation or Saltation/Suspension 28

2.4.2.4 Sand Cluster 29

2.4.2.5 Separated Moving Beds (Dunes) 29

2.4.2.6 Continuous Moving Beds (Dunes) 29

2.4.2.7 Stationary Bed 29

2.4.3 Mechanism of Cuttings Transport 30

2.5 Major Drilling Parameters Effects on Cuttings Transport 30

2.5.1 Parameters with Major Effects on Cuttings Transport 32

2.5.1.1 Pipe Rotation Speed Effect 32

2.5.1.2 Hole Inclination Effect 34

2.5.1.3 Mud Weight Effect 35

2.5.1.4 Annular Mud Velocity Effect (Mud Flow Rate) 35
2.5.2 Parameters with Moderate Effects on Cuttings Transport 36
2.5.2.1 Cuttings Size Effect 36
2.5.2.2 Mud Rheology Effect 37
2.5.2.3 Pipe Eccentricity Effect 37
2.6 Nanoparticles 40
2.6.1 Type and Classification of Nanomaterials 42
2.6.2 Silica Nanoparticles 43
2.6.3 Aluminium Oxide Nanoparticles 45
2.6.4 Copper (II) Oxide Nanoparticles 46
2.6.5 Magnesium Oxide Nanoparticles 48

CHAPTER 3 RESEARCH METHODOLOGY 53
3.1 Introduction 53
3.2 Methodology Flow Chart 53
3.3 Particle Size Analysis 54
3.4 Formulation of Drilling Muds Containing both WBM-Free Nanoparticles and WBM with Nanoparticles 55
3.5 Mud Weight Measurement 57
3.6 pH Determination 58
3.6.1 Viscosity Measurement 59
3.6.2 Gel Strength Measurement 62
3.7 Flow Loop Experimental System 63
3.7.1 Mud Tank 64
3.7.2 Mud Pump 65
3.7.3 Injection System for Cuttings 65
3.7.4 Cuttings Separation System 66
3.7.5 Drill Pipe Eccentricity System 66
3.7.6 Flow Rate Measurement Instrument 66
3.7.7 Inclination Angle Section 67
3.8 Simulated Drill Cuttings Preparation 67

	3.9	Cuttings Transport Experiment Procedure	68
CHAPTER 4		**RESULTS AND DISCUSSIONS**	**71**
	4.1	Introduction	71
	4.2	Mud Density of WBM-free NPs and WBM-containing NPs	71
	4.3	Mud pH of WBM-free NPs and WBM-containing NPs	72
	4.4	Rheological and filtration properties performance of various drilling muds	74
	4.4.1	Apparent Viscosity of WBM-free NPs and WBM-containing NPs	74
	4.4.2	Plastic Viscosity of WBM-free NPs and WBM-containing NPs	75
	4.4.3	Yield Point of WBM-free NPs and WBM-containing NPs	76
	4.4.4	10-Second Gel Strength of WBM-free NPs and WBM-containing NPs	78
	4.4.5	10-Minute Gel Strength of WBM-free NPs and WBM-containing NPs	79
	4.4.6	Filtrate Loss Volume of WBM-free NPs and WBM-containing NPs	81
	4.4.7	Filter Cake Thickness of WBM-free NPs and WBM-containing NPs	83
	4.5	Particle Size Distribution Analysis of Nanoparticles	86
	4.6	Zeta Potential Analysis of Nanoparticles	89
	4.7	Flow Dynamics of Drilling Muds in a Flow Loop with or without Pipe Eccentricity	91
	4.7.1	Effect of Nanoparticles Concentrations on Cuttings Transport Efficiency at a Concentric Drill Pipe	91
	4.7.2	Effect of Nanoparticles Concentrations on Cuttings Transport Efficiency at Eccentric Drill Pipe	98

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS 105

5.1 Conclusions 105

5.1.1 Determining the performance of rheological and filtration properties of WBM-free NPs and WBM with varying concentrations of SiO_2, Al_2O_3, CuO, and MgO NPs at 25 ^oC. 105

5.1.2 Determining and comparing between the cuttings transport performance of WBM-free NPs and WBM-containing NPs when the drill pipe was concentric. 106

5.1.3 Investigating the effect of drill pipe eccentricity on cuttings transport performance of WBM-free NPs and WBM-containing NPs at eccentric drill pipe of 1.0 107

5.2 Recommendations 108

REFERENCES 109

LIST OF PUBLICATIONS 121

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 2. 1	Applications of NPs and nanocomposites on cuttings transport and hole cleaning	49
Table 3. 1	Formulation of Drilling Muds	56
Table 4. 1	Mud properties results of WBM and WBM-with NPs measured under 25 ^{o}C	86

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 2.1	The content of WBMs in weight percentage (Neff, 2005).	12
Figure 2.2	Advantages and disadvantages of WBMs based on (Mellott, 2006), and (Apaleke et al., 2012).	12
Figure 2.3	Yield Point is a shear stress at zero shear rate (Ali et al., 2021).	16
Figure 2.4	Rheological behaviour of different types of fluids (Rehm et al., 2012).	19
Figure 2.5	Forces acting on a single cutting lying on the lower side of the borehole (Ford et al., 1996)	23
Figure 2.6	Horizontal well cuttings convey flow patterns (Khatibi et al., 2018)	27
Figure 2.7	Major parameters effecting on cuttings transport (Adari et al., 2000).	31
Figure 2.8	Degree of influencing parameters on cuttings transport (Sifferman & Becker, 1992).	32
Figure 2.9	The drilled cuttings in annulus section with (Helical or Whirling Motion) and without pipe rotation (Williams & Bruce, 1951).	33
Figure 2.10	Cuttings in drill pipe eccentricity in the directional well (Zhu et al., 2019).	39
Figure 2.11	Fluid velocity profile in eccentric annulus (Azouz et al., 1993).	40
Figure 2.12	Scale sizes of nanomaterials compared to common materials (Tanaka et al., 2005)	41
Figure 2.13	Alterations to the cube's surface area to volume ratio. The surface area to volume ratio of a cube (or other item) increases with decreasing size, and this has a significant impact on how a nanoscale substance interacts with its surroundings. (Pouran, 2018).	42
Figure 2.14	Dried colloidal SiO2 morphology under controlled and natural drying in the presence of water (Rahman & Padavettan, 2012).	44

Figure 2.15 Chemical structure of aluminium oxide (Anyanwu & Mustapha Unubi, 2016). 46
Figure 3.1 Methodology flowchart 54
Figure 3.2 Malvern nanoparticle size analyser 55
Figure 3.3 The conventional mud balance 57
Figure 3.4 Mud Weight Measurement 58
Figure 3.5 A pH Meter 59
Figure 3.6 Viscosity Measurement Steps 60
Figure 3.7 Fann viscometer 61
Figure 3.8 Gel Strength Measurement Procedure 63
Figure 3.9 Field-oriented Laboratory Cuttings Transport Flow Loop 64
Figure 3.10 A Stainless-Steel Mud Tank 65
Figure 3.11 Sieve Shaker 68
Figure 3.12 Laboratory oven 68
Figure 3.13 Field-Oriented Laboratory Cuttings Transport Flow Loop 70
Figure 4.1 Mud Density of Water-Based Mud with and without Nanoparticles 72
Figure 4.2 Mud pH of Water-Based Mud with and without Nanoparticles 73
Figure 4.3 Apparent Viscosity of Water-Based Mud with and without Nanoparticles 75
Figure 4.4 Plastic Viscosity of Water-Based Mud with and without Nanoparticles 76
Figure 4.5 Yield Point of Water-Based Mud with and without Nanoparticles 78
Figure 4.6 10-Second Gel Strength of Water-Based Mud with and without Nanoparticles 79
Figure 4.7 10-Minute Gel Strength of Water-Based Mud with and without Nanoparticles 80
Figure 4.8 Filtrate Loss Volume of Water-Based Mud with and without Nanoparticles 83
Figure 4.9 API Filter Cake Thickness of Water-Based Mud with and without Nanoparticles 85

Figure 4.10 Depiction of the Cake Thickness of all the Drilling Mud Samples 85

Figure 4.11 PSD result of SiO_2 NP. 87

Figure 4.12 PSD result of Al_2O_3 NP. 87

Figure 4.13 PSD result of MgO NP. 88

Figure 4.14 PSD result of CuO NP. 88

Figure 4.15 Zeta potential of aluminium oxide (Al_2O_3) 89

Figure 4.16 Zeta potential of magnesium oxide (MgO) 90

Figure 4.17 Zeta potential of silicon dioxide (SiO_2) 90

Figure 4.18 Zeta potential of copper oxide (CuO) 91

Figure 4.19 CTE of various mud samples evaluated with 0.26 wt.% of NPs at 0 ^{o} hole angle at three cutting sizes (a) sand 1 (1.0-1.4) mm (b) sand 2 (1.5-1.7) mm (c) sand 3 (1.8-2) mm and flowrates (1.9, 2.15, and 2.4 L/s) in a concentric drill pipe 94

Figure 4.20 CTE of various mud samples evaluated with 0.26 wt.% of NPs at 30 ^{o} hole angle at three cutting sizes (a) sand 1 (1.0-1.4) mm (b) sand 2 (1.5-1.7) mm (c) sand 3 (1.8-2) mm and flowrates (1.9, 2.15, and 2.4 L/s) in a concentric drill pipe 95

Figure 4.21 CTE of various mud samples evaluated with 0.26 wt.% of NPs at 60 ^{o} hole angle at three cutting sizes (a) sand 1 (1.0-1.4) mm (b) sand 2 (1.5-1.7) mm (c) sand 3 (1.8-2) mm and flowrates (1.9, 2.15, and 2.4 L/s) in a concentric drill pipe 96

Figure 4.22 CTE of various mud samples evaluated with 0.26 wt.% of NPs at 90 ^{o} hole angle at three cutting sizes (a) sand 1 (1.0-1.4) mm (b) sand 2 (1.5-1.7) mm (c) sand 3 (1.8-2) mm and flowrates (1.9, 2.15, and 2.4 L/s) in a concentric drill pipe 97

Figure 4.23 CTE of various mud samples evaluated with 0.26 wt.% of NPs at 0 ^{o} hole angle at three cutting sizes (a) sand 1 (1.0-1.4) mm (b) sand 2 (1.5-1.7) mm (c) sand 3 (1.8-2) mm and flowrates (1.9, 2.15, and 2.4 L/s) in an eccentric drill pipe 100

Figure 4.24 CTE of various mud samples evaluated with 0.26 wt.% of NPs at 30 ^{o} hole angle at three cutting sizes (a) sand 1 (1.0-1.4) mm (b) sand 2 (1.5-1.7) mm (c) sand 3 (1.8-2) mm and flowrates (1.9, 2.15, and 2.4 L/s) in an eccentric drill pipe. 101

Figure 4.25 CTE of various mud samples evaluated with 0.26 wt.% of NPs at 60 ^{o} hole angle at three cutting sizes (a) sand 1 (1.0-1.4) mm (b) sand 2 (1.5-1.7) mm (c) sand 3 (1.8-2) mm and flowrates (1.9, 2.15, and 2.4 L/s) in an eccentric drill pipe 102

Figure 4.26 CTE of various mud samples evaluated with 0.26 wt.% of NPs at 90 o hole angle at three cutting sizes (a) sand 1 (1.0-1.4) mm (b) sand 2 (1.5-1.7) mm (c) sand 3 (1.8-2) mm and flowrates (1.9, 2.15, and 2.4 L/s) in an eccentric drill pipe 103

LIST OF ABBREVIATIONS

ANN	-	Artificial Neural Network
GA	-	Genetic Algorithm
PSO	-	Particle Swarm Optimization
MTS	-	Mahalanobis Taguchi System
MD	-	Mahalanobis Distance
TM	-	Taguchi Method
UTM	-	Universiti Teknologi Malaysia
XML	-	Extensible Markup Language
ANN	-	Artificial Neural Network
GA	-	Genetic Algorithm
PSO	-	Particle Swarm Optimization

LIST OF SYMBOLS

δ	-	Minimal error
D, d	-	Diameter
F	-	Force
v	-	Velocity
p	-	Pressure
I	-	Moment of Inersia
r	-	Radius
Re	-	Reynold Number

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Due to rising energy needs and declining production, continuous work is needed to expand new technological frontiers in oilfield operations. It is not possible to extract the hydrocarbon reserves found lower than shale and close to the depletion stage using conventional techniques. As a result, unconventional hydrocarbon sources beneath must be drilled with creativity(Hassan, 2013). Because of the complicated behaviour related to the rheological characteristics of the drilling fluids under diverse drilling situations and environments, improved forming and engineering designing of the mud systems are essential to achieve a target of deep hydrocarbons reserves (Hassan, 2013). Different well types, including horizontal and deviated wells, are drilled to the pay zone to profitably extract oil and gas from reservoirs. Highly deviated wells, according to (Helms, 2008), have an inclination greater than 60° for the bulk of their length. Although drilling processes would need to be changed, it is possible to improve directional drilling methods to increase the inclination to 60–90°(Boyou et al., 2019). To drill these high-angle wells effectively, modifications to standard drilling rig equipment could also be necessary. A horizontal well is one that is dug at a 90° inclination and kept there for a long time. Horizontal wells are substantially more costly than normal deviated wells because they require specialized equipment and longer drilling times (Boyou et al., 2019).

The ineffectiveness of conventional muds for efficient drilling and hole-cleaning operations has been highlighted as in recent times when drilling in challenging situations, such as deep-water drilling operations and extended reach. Therefore, there is a need for innovative drilling fluids that can be effective in such circumstances (Boyou et al., 2019). To drill and produce safely and profitably, oil and gas operating and service companies are searching for many practical methods to handle challenging situations. Oil-based muds (OBMs) made by micronized barite, for instance, were studied in the North Sea (Kageson-Loe et al., 2007).

OBMs have shown encouraging results in shale inhibition, bit lubrication, and torque reduction(Rafati et al., 2018). Although, the use of OBMs in drilling operations is constrained in most drilling procedures due to their high procurement costs and treatment of hazardous waste. Water-based muds (WBMs) are currently preferred OBMs since they are more affordable and accepted by the environment (Rafati et al., 2018).

Initial drilling lubricant utilized during the operations of drilling was water (Brantly & Carter, 1961). Oil wells can be dug using just water; however, under static conditions, drilled cuttings cannot be suspended. Additionally, Absolutely not thick enough to maintain formation pressure and is unable to build an acceptable low-permeable layer on top of permeable formations (BOYOU, 2019). In recent years, WBMs have included a range of additives. Examples of these include barite and clay, as well as other insoluble weighing components including alkalis, salts, surfactants, organic polymers in colloidal solutions, and others. The type of formation to be drilled, the presence of dispersive minerals at the formation, so the cost all influence the choice of additives (BOYOU, 2019). Heavy muds were developed by addition of dense minerals to enhance mud weight for the control of pressure, leading to advancements in WBMs. The market for heavy mud was created by increased drilling activity. WBMs, however, have problems of low stability and drilled cuttings lifting capability limitation (Islam & Hossain, 2020). When drilling in shale formation, the clay can easily disperse and swell in WBMs (Islam & Hossain, 2020).

According to (Hall et al., 1950),removing cutting and sloughs is one of the drilling fluids' most crucial features. Drilled cuttings must be removed, especially in horizontal wells. Inadequate hole cleaning raises the potential for drilled pipe to be trapped in addition to limiting penetration rates because of accumulation of drilling cuttings in the pore hole. Wellbore cleaning is significantly impacted by mud rheology (Hakim et al., 2018). However, prior studies' findings on mud rheological properties and its effectiveness in the cleaning of the hole process have been contradictory. High viscosity values, according to (Peden et al., 1990), improve cuttings circulation capabilities in the deviated wells. However, (Kelessidis et al., 2007) found whether it improves drilling mud viscosity in horizontal wells reduced hole cleaning effectiveness. This paradox may be brought on by the viscosity-induced transition from turbulent to laminar flow, which lessens the drilling fluid's capacity to clean the wellbore. Given that the flow regime is turbulent, (Walker & Li, 2000) stated that the results of (Kageson-Loe et al., 2007) in another study. They discovered that this condition works best in wellbore configurations that are horizontal or slightly inclined. They suggested that vertical or slightly inclined wellbores be drilled with a high viscosity drilling fluids that has a laminar flow regime.

For the next following drilling fluid slurries, the cuttings' dynamic behaviour is influenced by their size and structure. Cuttings' size and properties in drilling fluids affect how quickly they are removed from the hole and brought to the surface. The effect of different size of cuttings to efficiently clean the hole process has been the subject of several studies. Although earlier investigations (Peden et al., 1990) and (Walker & Li, 2000) found as the cuttings smaller in size so it is more difficult to transport, (Martins et al., 1996) discovered that larger cuttings are more difficult to circulate to the top. However, smaller cuttings can be transported to the surface more effectively if the drilling fluid's viscosity and rotation speed are high (Sanchez et al., 1997). (Shadizadeh & Zoveidavianpoor, 2012) discovered that as the size of the cuttings increases, the lowest transit speed needed for rolling and circulation of cuttings decreases. Accordingly, less size of cuttings are therefore easier to transport in terms of minimum transit velocity.

When drilling, particularly in inclined areas of a hole, gravity forces the drill string to rest on the low side of the borehole. Because of the extremely low fluid velocity, this introduces an eccentrically tight gap in the annulus the lower part of the drill pipe (Pang et al., 2019).The drilling fluids' capability to circulate cuttings to the surface in this area of the annulus will be constrained. The particle and fluid velocities of the small gap decrease as eccentricity increases, especially with high-viscosity fluids (Boyou et al., 2019). But given that well trajectories during drilling operations affect pipe eccentricity, such detrimental influnces on the hole-cleaning operations could be preventable. As a result, the effectiveness of cuttings removal decreases as pipes become less concentrically spaced (Boyou et al., 2019).

Rotating velocity is more efficient in slanted wells than in vertical wells(Sanchez et al., 1997). This means that rotating drill pipes can improve cuttings conveyance on the constrained side of an eccentric wellbore. According to (Busch & Johansen, 2020), the best conditions for effectively executing pipe rotation are low penetration rates and small cuttings for severely deviated wellbores. Beyond a certain spinning speed, Taylor vortices can also aid in increasing the effectiveness of lifting horizontal sections (Sanchez et al., 1997). As a result, when removing microscopic drilled cuttings, the drill pipe rotation factor is critical to consider(Cayeux et al., 2014).

Fluid efficiency in drilling in carrying cuttings may be impacted by pipe eccentricity. The conveyance of cuttings is significantly impacted by the pipe's location within the annulus. The average velocity of the mud slurry in the annulus is influenced by drilling pipe eccentricity. Some of the variables that are altered are the carrying capacity index, cut-off concentration, transport velocity, and equivalent circulating density (ECD). When diverging from a concentric annulus with 0% eccentricity to partial eccentric annulus with 50% eccentricity and to a fully eccentric of 100%, cuttings transport is thought to be less effective. Furthermore, when the gap among the fracture pressure and the pressure of the formation is very small, excessive eccentricity can lead to significant fluid loss after formation breaking (Ozbayoglu et al., 2010). According to (Epelle & Gerogiorgis, 2017), greater cuttings conveyance results from decreased cuttings concentration once the pipe of drilling is concentric with the borehole. However, eccentric causes the drilled cuttings and fluid velocities to drop in the small gap, particularly for viscous fluid; therefore, eccentric has to be studied.

When the annulus diverges from concentric to eccentric, the number of cuttings accumulation increases (Nazari et al., 2010). Cutting removal in deviated holes may be more successful than in vertical holes due to pipe rotation and eccentricity. This is due to the fact that the mud's ability to flow is enhanced by the average fluid velocity and mechanical action that causes the pipe to spin (Heydari et al., 2017). These elements might have a big impact on how cuttings are moved using drilling muds (Heshamudin et al., 2019). (Ozbayoglu et al., 2008) investigated how pipe rotation affects CTE in holes with deviating and horizontal axes. They noticed that moving the drill pipe in a circular motion greatly enhanced cutting conveyance.

(Mahmoud et al., 2020) used a multiphase flow system by several air and water flow rates to inject different quantities of cuttings into an experimental rig to study the motions of flow in the hole-cleaning operation. They discovered that frictional pressure losses may be quite well anticipated by comparing experimental data to recognised models.(Ogunrinde & Dosunmu, 2012) found important elements that affect cutting transport and bit hydraulics at various inclination degrees in a separate study. To save unproductive time, they created a prototype for forecasting the ideal flow rate as well as the rate of penetration.

Similarly, to this, (Guan et al., 2016) uses the multi-dimensional ant colony approach to examine different hole-cleaning parameters in horizontal wells to enhance drilling operations. They discovered that when rising the rate of the flow and pressure-bearing capacity of the system can improve horizontal good hole cleaning. To improve the mud-lifting capabilities of water-based drilling fluids, (Boyou et al., 2018) tried polymer beads (polypropylene). They used various cutting sizes to evaluate cutting transport effectiveness in inclined static annuli and discovered that small size cuttings moved more effectively than big size cuttings because of the drag force on cuttings created by polymer beads. As opposed to that,, as cutting sizes reached bead size, the effectiveness of cuttings transport declined.

Recently, the use of nanomaterials has become more widespread, especially among scientists. Petroleum development and production benefit from the wide range of uses of nanomaterials oil and gas industry and reservoir protection (Belavadi & Chukwu, 1994). Studies indicate that the use of nanoparticles (NPs) greatly enhances the rheology of water-based drilling muds (Ariffin & Amir, 2011). (Irfan, 2016) discovered that regarding the cooling of bit, torque and drag reducing, viscous behaviour, and low friction factors, nano-drilling fluids found to outperform traditional drilling fluids.

(Irfan, 2016) found that in terms of cooling of bit, torque and drag reduction, viscous behaviour, and low friction factors, nano-drilling fluids performed better than conventional drilling fluids. A number of experiments that added nanoparticles including silica, carbon nanotubes, and aluminium oxide to water-based muds also showed improvements in thermal stability up to 160 °C (Kang & Li, 2011) .(Hoelscher et al., 2013) reduced pressure transmission in shale by physically plugging Marcellus and Manco's shale pores with nanoscale silica. The use of nanomaterials for fluid loss, rheological properties augmentation, and other reasons has been detailed in other studies that are outside the purview of this study. An extensive review of these efforts may be found elsewhere. In general, nanoparticles were used to solve a variety of drilling fluid challenges, including mud thermal stability at high temperatures, mud cake thickness, and filtrate volume reduction (Jain et al., 2015).

1.2 Problem Statement

Conventional WBMs confront severe and difficult formations, such as deep and ultra-deep formations and high temperature and high pressure (HTHP) conditions, which result in limited temperature stability and thermal degradation of the drilling mud above 257–266 oF (125–130 °C) (Yang et al., 2017). As a result, conventional WBMs are unable to perform their necessary role in the drilling process properly, including lifting drilled cuttings from the bottom of the hole to the surface and protecting the formation from drilling fluid intrusion. Therefore, WBMs should be formulated with NPs, which have been found to be extremely stable in deeper drilling depths and extreme downhole conditions. This will prevent the degradation of conventional WBMs under challenging drilling conditions and ensure that they continue to perform their functions of lifting drilled cuttings to the surface and ensuring minimal fluid loss into the drilled formation (Boyou et al., 2019) (Jokandan et al., 2016).

There has been a lot of research recently on the use of NPs to improve the rheological characteristics of drilling fluids, but none on how to enhance cuttings transport in the wellbore, with the exception of nanosilica (SiO2 NP) (Boyou et al., 2019) and multi-walled carbon nanotubes (MWCNTs) (Ariffin & Amir, 2011). The use of these SiO2 NP and MWCNTs, however, does not account for the effect of pipe eccentricity on cuttings transport performance, which could be necessary for efficient hole cleaning. Additionally, no laboratory research has been carried out on how alumina (Al_2O_3), copper oxide (CuO), and magnesium oxide (MgO) perform in the transfer of cuttings from the hole to the surface in a laboratory flow loop that is field-oriented. Therefore, using various WBM formulations containing SiO_2, Al_2O_3, CuO, and MgO NPs, this study investigated the effects of pipe eccentricity along with other drilling parameters such as pipe rotation, fluid velocity, cuttings size, and hole angle on the cuttings transport process.

1.3 Research Questions

The following research questions were used to guide the execution of this study:

(a) How do SiO_2, Al_2O_3, CuO, and MgO modify the rheological and filtration characteristics of the conventional WBM system?

(b) Does the presence of SiO_2, Al_2O_3, CuO, and MgO alter the conventional WBM system's ability to transport cuttings?

(c) Does pipe eccentricity influence the efficiency of conventional WBM in the cutting transport process?

1.4 Research Objectives

The general aim of this study is to examine the performance of WBM in lifting drilled cuttings out of the hole to the surface using different NPs. This goal was met by completing the following tasks:

(1) To determine the performance of rheological and filtration properties of WBM-free NPs and WBM with varying concentrations of SiO2, Al2O3, CuO, and MgO NPs at 25 °C.

(2) To determine and compare between the cuttings transport performance of WBM-free NPs and WBM-containing NPs when the drill pipe eccentricity is concentric and fully eccentric.

1.5 Scope of the Study

(1) Formulation of a conventional WBM system without NPs.

(2) Formulation of NP-based drilling muds by adding 0.13 wt.% and 0.26 wt.% of SiO2 NP, Al2O3 NP, CuO NP, and MgO NP into conventional WBM.

(3) Measurement of the rheological properties (plastic viscosity, yield point, gel strength), pH, and density of all the formulated drilling mud systems at a low temperature of 25 °C.

(4) Measurement of the filtration properties (fluid loss volume and filter cake thickness) of all the formulated drilling mud systems at low pressure and low temperature (LPLT) conditions of 100 psi and 25 oC, respectively.

(5) Determining the cuttings transport performance of the WBM-free NPs and the WBMs containing NPs using NP optimum concentrations cuttings sizes of 1.0–

1.4 mm, 1.5–1.7 mm, and 1.8–2.0 mm, hole angles of 0, 30, 60, and 90o at varied flowrates of 1.9 L/s, 2.15 L/s and 2.4 L/s in a concentric drill pipe (eccentricity, e = 0).

(6) Determining the cuttings transport performance of the WBM-free NPs and the WBMs containing NPs using NP optimum concentrations cuttings sizes of 1.0–1.4 mm, 1.5–1.7 mm, and 1.8–2.0 mm, hole angles of 0, 30, 60, and 90o at varied flowrates of 1.9 L/s, 2.15 L/s and 2.4 L/s in a concentric drill pipe (eccentricity, e = 1.0).

1.6 Significant of the Study and Contribution to Knowledge

This study is significant and can contribute to knowledge in the following ways:

(1) To overcome the limitations of conventional WBM at high temperature conditions.

(2) To increase the efficiency of drilling operation with improvement in cuttings transport process by using less-viscous and dispersible drilling fluid of NPs.

(3) The cuttings transport performance of WBM could be simpler with NPs thereby improving the drilling process for greater oil productivity and reduced drilling time and cost.

(4) The incorporation of the NPs into conventional WBMs may contribute to the addition of new knowledge on drilled cuttings recovery at the surface.

REFERENCES

Abbas, A. K., Alsaba, M. T., & Al Dushaishi, M. F. (2021). Improving hole cleaning in horizontal wells by using nanocomposite water-based mud. *Journal of Petroleum Science and Engineering, 203*, 108619.

Adari, R. B., Miska, S., Kuru, E., Bern, P., & Saasen, A. (2000). Selecting drilling fluid properties and flow rates for effective hole cleaning in high-angle and horizontal wells. SPE Annual Technical Conference and Exhibition,

Aftab, A., Ismail, A. R., Ibupoto, Z., Akeiber, H., & Malghani, M. (2017). Nanoparticles based drilling muds a solution to drill elevated temperature wells: A review. *Renewable and Sustainable Energy Reviews, 76*, 1301-1313.

Akpan, E. U. (2019). *Water-based drilling fluids for high temperature and dispersible shale formation applications*. University of Salford (United Kingdom).

Ali, I., Ahmad, M., & Ganat, T. (2021). Development of a new formulation for enhancing the rheological and filtration characteristics of low-solids WBMs. *Journal of Petroleum Science and Engineering, 205*, 108921.

Alther, G. (1987). The qualifications of bentonite as a soil sealant. *Engineering Geology, 23*(3-4), 177-191.

Anyanwu, C., & Mustapha Unubi, M. (2016). Experimental evaluation of particle sizing in drilling fluid to minimize filtrate losses and formation damage. SPE Nigeria Annual International Conference and Exhibition,

Apaleke, A. S., Al-Majed, A., & Hossain, M. E. (2012). Drilling fluid: state of the art and future trend. North Africa technical conference and exhibition,

Ariffin, S., & Amir, H. (2011). Water based mud lifting capacity improvement by multiwall carbon nanotubes additive. *Journal of Petroleum and Gas Engineering, 5*(2), 99-107.

Azouz, I., Shirazi, S. A., Pilehvari, A., & Azar, J. (1993). Numerical simulation of laminar flow of yield-power-law fluids in conduits of arbitrary cross-section.

Bayat, A. E., Moghanloo, P. J., Piroozian, A., & Rafati, R. (2018). Experimental investigation of rheological and filtration properties of water-based drilling fluids in presence of various nanoparticles. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 555*, 256-263.

Belavadi, M. N., & Chukwu, G. (1994). Experimental study of the parameters affecting cutting transportation in a vertical wellbore annulus. SPE Western Regional Meeting,

Bilgesu, H. I., Mishra, N., & Ameri, S. (2007). Understanding the effect of drilling parameters on hole cleaning in horizontal and deviated wellbores using computational fluid dynamics. Eastern Regional Meeting,

BOYOU, N. V. (2019). *NANOSILICA-ENHANCED WATER-BASED DRILLING MUD FOR HOLE CLEANING IN INCLINED WELLS* Universiti Teknologi Malaysia].

Boyou, N. V., Ismail, I., Hamzah, M. H., & Uche, O. M. D. (2018). Polypropylene beads in water-based mud for cuttings transportation improvement. *Chemical Engineering Transactions, 63*, 787-792.

Boyou, N. V., Ismail, I., Sulaiman, W. R. W., Haddad, A. S., Husein, N., Hui, H. T., & Nadaraja, K. (2019). Experimental investigation of hole cleaning in directional drilling by using nano-enhanced water-based drilling fluids. *Journal of Petroleum Science and Engineering, 176,* 220-231.

Brantly, J., & Carter, D. (1961). Hydraulic rotary system. *History of petroleum engineering. American Petroleum Institute, New York*, 271-452.

Briscoe, B., Luckham, P., & Ren, S. (1994). The properties of drilling muds at high pressures and high temperatures. *Philosophical Transactions of the Royal Society of London. Series A: Physical and Engineering Sciences*, *348*(1687), 179-207.

Busch, A., & Johansen, S. T. (2020). Cuttings transport: On the effect of drill pipe rotation and lateral motion on the cuttings bed. *Journal of Petroleum Science and Engineering*, *191*, 107136.

Caenn, R., Darley, H. C., & Gray, G. R. (2011). *Composition and properties of drilling and completion fluids*. Gulf professional publishing.

Cayeux, E., Mesagan, T., Tanripada, S., Zidan, M., & Fjelde, K. K. (2014). Real-time evaluation of hole-cleaning conditions with a transient cuttings-transport model. *SPE Drilling & Completion, 29*(01), 5-21.

Chesser, B., Clark, D., & Wise, W. (1994). Dynamic and static filtrate-loss techniques for monitoring filter-cake quality improves drilling-fluid performance. *SPE Drilling & Completion, 9*(03), 189-192.

Cho, H., Shah, S. N., & Osisanya, S. O. (2000). A three-segment hydraulic model for cuttings transport in horizontal and deviated wells. SPE/CIM International Conference on Horizontal Well Technology,

Cinku, K., Karakas, F., & Boylu, F. (2014). Effect of calcinated magnesite on rheology of bentonite suspensions. Magnesia-bentonite interaction. *Physicochemical Problems of Mineral Processing, 50*(2), 453--466.

Crumpton, H. (2018). *Well control for completions and interventions*. Gulf Professional Publishing.

Davoodi, S., SA, A. R., Soleimanian, A., & Jahromi, A. F. (2019). Application of a novel acrylamide copolymer containing highly hydrophobic comonomer as filtration control and rheology modifier additive in water-based drilling mud. *Journal of Petroleum Science and Engineering, 180*, 747-755.

Ebikapaye, J. (2018). Effects of temperature on the density of water based drilling mud. *Journal of Applied Sciences and Environmental Management, 22*(3), 406-408.

Egenti, N. B. (2014). Understanding drill-cuttings transportation in deviated and horizontal wells. SPE Nigeria annual international conference and exhibition,

Einstein, A. (1956). *Investigations on the Theory of the Brownian Movement*. Courier Corporation.

Elochukwu, H., Gholami, R., & Dol, S. S. (2017). An approach to improve the cuttings carrying capacity of nanosilica based muds. *Journal of Petroleum Science and Engineering, 152*, 309-316.

Epelle, E. I., & Gerogiorgis, D. I. (2017). A multiparametric CFD analysis of multiphase annular flows for oil and gas drilling applications. *Computers & Chemical Engineering, 106*, 645-661.

Esmaeili, A. (2011). Applications of nanotechnology in oil and gas industry. AIP conference proceedings,

Ford, J. T., Gao, E., Oyeneyin, M., Peden, J., Larrucia, M., & Parker, D. (1996). A new MTV computer package for hole-cleaning design and analysis. *SPE Drilling & Completion, 11*(03), 168-172.

Gautam, S., Guria, C., & Rajak, V. K. (2022). A state of the art review on the performance of high-pressure and high-temperature drilling fluids: Towards understanding the structure-property relationship of drilling fluid additives. *Journal of Petroleum Science and Engineering*, 110318.

Gbadamosi, A. O., Junin, R., Oseh, J. O., Agi, A., Yekeen, N., Abdalla, Y., Ogiriki, S. O., & Yusuff, A. S. (2018). Improving hole cleaning efficiency using nanosilica in water-based drilling mud. SPE Nigeria annual international conference and exhibition,

Guan, Z.-c., Liu, Y.-m., Liu, Y.-w., & Xu, Y.-q. (2016). Hole cleaning optimization of horizontal wells with the multi-dimensional ant colony algorithm. *Journal of Natural Gas Science and Engineering, 28*, 347-355.

Hakim, H., Katende, A., Sagala, F., Ismail, I., & Nsamba, H. (2018). Performance of polyethylene and polypropylene beads towards drill cuttings transportation in horizontal wellbore. *Journal of Petroleum Science and Engineering, 165*, 962-969.

Hall, H., Thompson, H., & Nuss, F. (1950). Ability of drilling mud to lift bit cuttings. *Journal of Petroleum Technology, 2*(02), 35-46.

Hassan, A. (2013). Review of the global oil and gas industry: a concise journey from ancient time to modern world. *Petroleum Technology Development Journal, 3*(2), 123-141.

Helms, L. (2008). Horizontal drilling. *North Dakota Department of Mineral Resources Newsletter, 35*(1), 1-3.

Heshamudin, N. S., Katende, A., Rashid, H. A., Ismail, I., Sagala, F., & Samsuri, A. (2019). Experimental investigation of the effect of drill pipe rotation on improving hole cleaning using water-based mud enriched with polypropylene beads in vertical and horizontal wellbores. *Journal of Petroleum Science and Engineering, 179*, 1173-1185.

Heydari, O., Sahraei, E., & Skalle, P. (2017). Investigating the impact of drillpipe's rotation and eccentricity on cuttings transport phenomenon in various horizontal annuluses using computational fluid dynamics (CFD). *Journal of Petroleum Science and Engineering, 156*, 801-813.

Hoelscher, K. P., Young, S., Friedheim, J., & De Stefano, G. (2013). Nanotechnology application in drilling fluids. Offshore Mediterranean Conference and Exhibition,

Iler, R. K. (1955). *The colloid chemistry of silica and silicates* (Vol. 80). LWW.

Irfan, Y. (2016). *Study of viscosity and friction factor of nano drilling fluids along with torque and drag reduction* University of Stavanger, Norway].

Islam, M. R., & Hossain, M. E. (2020). *Drilling Engineering: Towards Achieving Total Sustainability*. Gulf Professional Publishing.

Ismail, A., Hassan, Z., & Mazen, A. (2002). Drilling fluids and wellbore cleaning technology. Proceedings of the Regional Symposium of Chemical Engineering, Petaling Jaya, Malaysia,

Jain, R., Mahto, T. K., & Mahto, V. (2016). Rheological investigations of water based drilling fluid system developed using synthesized nanocomposite. *Korea-Australia Rheology Journal, 28*(1), 55-65.

Jain, R., Mahto, V., & Sharma, V. (2015). Evaluation of polyacrylamide-grafted-polyethylene glycol/silica nanocomposite as potential additive in water based drilling mud for reactive shale formation. *Journal of Natural Gas Science and Engineering, 26*, 526-537.

Javeri, S. M., Haindade, Z. W., & Jere, C. B. (2011). Mitigating loss circulation and differential sticking problems using silicon nanoparticles. SPE/IADC Middle East Drilling Technology Conference and Exhibition,

Jeevanandam, J., Barhoum, A., Chan, Y. S., Dufresne, A., & Danquah, M. K. (2018). Review on nanoparticles and nanostructured materials: history, sources, toxicity and regulations. *Beilstein journal of nanotechnology, 9*(1), 1050-1074.

Jokandan, E. F., Naeiji, P., & Varaminian, F. (2016). The synergism of the binary and ternary solutions of polyethylene glycol, polyacrylamide and Hydroxyethyl cellulose to methane hydrate kinetic inhibitor. *Journal of Natural Gas Science and Engineering, 29*, 15-20.

Kageson-Loe, N. M., Massam, J., Prebensen, O. I., Van Der Zwaag, C., Taugbol, K., & Omland, T. H. (2007). Formation-damage observations on oil-based-fluid systems weighted with treated micronized barite. European Formation Damage Conference,

Kang, H. Y., & Li, G. J. (2011). Preparation and study of polyethylene glycol (PEG)/titanium dioxide (TiO2) phase change materials. Advanced Materials Research,

Karagüzel, C., Çetinel, T., Boylu, F., Çinku, K., & Çelik, M. (2010). Activation of (Na, Ca)-bentonites with soda and MgO and their utilization as drilling mud. *Applied Clay Science, 48*(3), 398-404.

Kelessidis, V., Bandelis, G., & Li, J. (2007). Flow of dilute solid-liquid mixtures in horizontal concentric and eccentric annuli. *Journal of Canadian Petroleum Technology, 46*(05).

Khataniar, S., Chukwu, G. A., & Xu, H. (1994). Evaluation of rheological models and application to flow regime determination. *Journal of Petroleum Science and Engineering, 11*(2), 155-164.

Khatibi, M., Time, R. W., & Shaibu, R. (2018). Dynamical feature of particle dunes in Newtonian and shear-thinning flows: relevance to hole-cleaning in pipe and annulus. *International Journal of Multiphase Flow, 99*, 284-293.

Kong, M., Zhang, W., Yang, Z., Weng, S., & Chen, Z. (2011). Facile synthesis of CuO hollow nanospheres assembled by nanoparticles and their electrochemical performance. *Applied surface science, 258*(4), 1317-1321.

Larsen, T., Pilehvari, A., & Azar, J. (1997). Development of a new cuttings-transport model for high-angle wellbores including horizontal wells. *SPE Drilling & Completion, 12*(02), 129-135.

Lucky, A. P. A., & Johnson, F. A. (2018). Modification of Bingham plastic rheological model for better rheological characterization of synthetic based drilling mud. *Journal of Engineering and Applied Sciences, 13*(10), 3573-3581.

Mahmoud, H., Hamza, A., Nasser, M. S., Hussein, I. A., Ahmed, R., & Karami, H. (2020). Hole cleaning and drilling fluid sweeps in horizontal and deviated wells: Comprehensive review. *Journal of Petroleum Science and Engineering, 186*, 106748.

Mao, H., Qiu, Z., Shen, Z., & Huang, W. (2015). Hydrophobic associated polymer based silica nanoparticles composite with core–shell structure as a filtrate reducer for drilling fluid at utra-high temperature. *Journal of Petroleum Science and Engineering, 129*, 1-14.

Martins, A., Sa, C., Lourenco, A., & Campos, W. (1996). Optimizing cuttings circulation in horizontal well drilling. International Petroleum Conference and Exhibition of Mexico,

Mellott, J. (2006). Technological improvements in wells drilled with a pneumatic fluid. IADC/SPE Drilling Conference,

Mir, M. R. (2017). *Investigation of the transport mechanism of the cutting transport in drilling horizontal wells using high speed camera and PIV for analysis* University of Stavanger, Norway].

Mohamadian, N., Ghorbani, H., Wood, D. A., & Khoshmardan, M. A. (2019). A hybrid nanocomposite of poly (styrene-methyl methacrylate-acrylic acid)/clay as a novel rheology-improvement additive for drilling fluids. *Journal of Polymer Research, 26*(2), 1-14.

Mohamed, A., Salehi, S., & Ahmed, R. (2021). Significance and complications of drilling fluid rheology in geothermal drilling: A review. *Geothermics, 93*, 102066.

Mohammadsalehi, M., & Malekzadeh, N. (2011). Optimization of hole cleaning and cutting removal in vertical, deviated and horizontal wells. SPE Asia Pacific Oil and Gas Conference and Exhibition,

Naderi, M. E., Khavarpour, M., Fazaeli, R., & Ghadi, A. (2022). Improving the fluid loss and rheological characteristics of Oil-based drilling fluid by using Copper Oxide nanoparticles. *International Journal of Nano Dimension, 13*(2), 205-213.

Nazari, T., Hareland, G., & Azar, J. J. (2010). Review of cuttings transport in directional well drilling: systematic approach. SPE western regional meeting,

Ofei, T. N., & Alhemyari, S. A. (2015). Computational fluid dynamics simulation of the effect of drill pipe rotation on cuttings transport in horizontal wellbores using a Newtonian fluid. 2015 International Field Exploration and Development Conference (IFEDC 2015),

Ogunrinde, J., & Dosunmu, A. (2012). Hydraulics optimization for efficient hole cleaning in deviated and horizontal wells. Nigeria annual international conference and exhibition,

Ohenhen, I., Ogiriki, S., Imuetiyan, I., & Ezeja, O. (2018). Experimental study of temperature effect on drilling mud with local additives. International Journal of Engineering Research in Africa,

Okrajni, S. S., & Azar, J. (1986). The effects of mud rheology on annular hole cleaning in directional wells. *SPE drilling engineering, 1*(04), 297-308.

Oku, T., Motoyoshi, R., Fujimoto, K., Akiyama, T., Jeyadevan, B., & Cuya, J. (2011). Structures and photovoltaic properties of copper oxides/fullerene solar cells. *Journal of Physics and Chemistry of Solids, 72*(11), 1206-1211.

Oseh, J. O., Mohd Norddin, M., Ismail, I., Gbadamosi, A. O., Agi, A., & Ismail, A. R. (2020). 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.

Ozbayoglu, M., Sorgun, M., Saasen, A., & Svanes, K. (2010). Hole cleaning performance of light-weight drilling fluids during horizontal underbalanced drilling. *Journal of Canadian Petroleum Technology, 49*(04), 21-26.

Ozbayoglu, M. E., Saasen, A., Sorgun, M., & Svanes, K. (2008). Effect of pipe rotation on hole cleaning for water-based drilling fluids in horizontal and deviated wells. IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition,

Pang, B., Wang, S., Jiang, X., & Lu, H. (2019). Effect of orbital motion of drill pipe on the transport of non-Newtonian fluid-cuttings mixture in horizontal drilling annulus. *Journal of Petroleum Science and Engineering, 174*, 201-215.

Peden, J., Ford, J., and, & Oyeneyin, M. (1990). Comprehensive experimental investigation of drilled cuttings transport in inclined wells including the effects of rotation and eccentricity. European Petroleum Conference,

Pilehvari, A. A., Azar, J., & Shirazi, S. A. (1999). State-of-the-art cuttings transport in horizontal wellbores. *SPE Drilling & Completion, 14*(03), 196-200.

Piroozian, A., Ismail, I., Yaacob, Z., Babakhani, P., & Ismail, A. S. I. (2012). Impact of drilling fluid viscosity, velocity and hole inclination on cuttings transport in horizontal and highly deviated wells. *Journal of Petroleum Exploration and Production Technology*, *2*(3), 149-156.

Ponmani, S., Nagarajan, R., & Sangwai, J. S. (2016). Effect of nanofluids of CuO and ZnO in polyethylene glycol and polyvinylpyrrolidone on the thermal, electrical, and filtration-loss properties of water-based drilling fluids. *SPE Journal*, *21*(02), 405-415.

Pouran, H. M. (2018). Engineered nanomaterials in the environment, their potential fate and behaviour and emerging techniques to measure them. *Handbook of environmental materials management*, 1-15.

Rafati, R., Smith, S. R., Haddad, A. S., Novara, R., & Hamidi, H. (2018). Effect of nanoparticles on the modifications of drilling fluids properties: A review of recent advances. *Journal of Petroleum Science and Engineering, 161*, 61-76.

Rahman, I. A., & Padavettan, V. (2012). Synthesis of silica nanoparticles by sol-gel: size-dependent properties, surface modification, and applications in silica-polymer nanocomposites—a review. *Journal of Nanomaterials, 2012*.

Ranjbar, R. (2010). *Cuttings transport in inclined and horizontal wellbore* University of Stavanger, Norway].

Rehm, B., Haghshenas, A., Paknejad, A., Al-Yami, A., Hughes, J., & Schubert, J. (2012). Flow drilling: underbalance drilling with liquid single-phase systems. *Underbalanced drilling: Limits and extremes*, 39-108.

Reverchon, E., & Adami, R. (2006). Nanomaterials and supercritical fluids. *The Journal of supercritical fluids, 37*(1), 1-22.

Robertson, R., & Stiff, H. (1976). An improved mathematical model for relating shear stress to shear rate in drilling fluids and cement slurries. *Society of Petroleum Engineers Journal, 16*(01), 31-36.

Rooki, R., Ardejani, F. D., Moradzadeh, A., Mirzaei, H., Kelessidis, V., Maglione, R., & Norouzi, M. (2012). Optimal determination of rheological parameters for herschel-bulkley drilling fluids using genetic algorithms (GAs). *Korea-Australia Rheology Journal, 24*(3), 163-170.

Sanchez, R. A., Azar, J., Bassal, A., & Martins, A. (1997). The effect of drillpipe rotation on hole cleaning during directional well drilling. SPE/IADC drilling conference,

Sang, S., Li, W., Pu, J., & Jian, L. (2008). Novel Al2O3-based compressive seals for IT-SOFC applications. *Journal of Power Sources, 177*(1), 77-82.

Sankar, R., Manikandan, P., Malarvizhi, V., Fathima, T., Shivashangari, K. S., & Ravikumar, V. (2014). Green synthesis of colloidal copper oxide nanoparticles using Carica papaya and its application in photocatalytic dye degradation. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 121*, 746-750.

Sarafraz, M., & Hormozi, F. (2014). Scale formation and subcooled flow boiling heat transfer of CuO–water nanofluid inside the vertical annulus. *Experimental Thermal and Fluid Science, 52*, 205-214.

Schaanning, M. T., Trannum, H. C., Øxnevad, S., Carroll, J., & Bakke, T. (2008). Effects of drill cuttings on biogeochemical fluxes and macrobenthos of marine sediments. *Journal of Experimental Marine Biology and Ecology, 361*(1), 49-57.

Shadizadeh, S., & Zoveidavianpoor, M. (2012). An experimental modeling of cuttings transport for an Iranian directional and horizontal well drilling. *Petroleum science and technology, 30*(8), 786-799.

Sifferman, T., & Becker, T. (1992). Hole cleaning in full-scale inclined wellbores. *SPE drilling engineering, 7*(02), 115-120.

Smith, S. R., Rafati, R., Haddad, A. S., Cooper, A., & Hamidi, H. (2018). Application of aluminium oxide nanoparticles to enhance rheological and filtration properties of water based muds at HPHT conditions. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 537*, 361-371.

Song, X., Xu, Z., Wang, M., Li, G., Shah, S. N., & Pang, Z. (2017). Experimental study on the wellbore-cleaning efficiency of microhole-horizontal-well drilling. *SPE Journal, 22*(04), 1189-1200.

Tanaka, T., Kozako, M., Fuse, N., & Ohki, Y. (2005). Proposal of a multi-core model for polymer nanocomposite dielectrics. *IEEE transactions on dielectrics and electrical insulation, 12*(4), 669-681.

Teo, C.-H., Zhu, Y., Gao, X., Wee, A. T.-S., & Sow, C.-H. (2008). Field emission from hybrid CuO and CuCO3 nanosystems. *Solid state communications, 145*(5-6), 241-245.

Vaseem, M., Umar, A., Kim, S. H., & Hahn, Y.-B. (2008). Low-temperature synthesis of flower-shaped CuO nanostructures by solution process: formation mechanism and structural properties. *The Journal of Physical Chemistry C, 112*(15), 5729-5735.

Vert, M., Doi, Y., Hellwich, K.-H., Hess, M., Hodge, P., Kubisa, P., Rinaudo, M., & Schué, F. (2012). Terminology for biorelated polymers and applications (IUPAC Recommendations 2012). *Pure and Applied Chemistry, 84*(2), 377-410.

Vipulanandan, C., & Mohammed, A. (2014). Hyperbolic rheological model with shear stress limit for acrylamide polymer modified bentonite drilling muds. *Journal of Petroleum Science and Engineering, 122*, 38-47.

Vryzas, Z., Mahmoud, O., Nasr-El-Din, H. A., & Kelessidis, V. C. (2015). Development and testing of novel drilling fluids using Fe2O3 and SiO2 nanoparticles for enhanced drilling operations. International petroleum technology conference,

Walker, S., & Li, J. (2000). The effects of particle size, fluid rheology, and pipe eccentricity on cuttings transport. SPE/ICOTA coiled tubing roundtable, Wang, Z.-m., & Long, Z.-h. (2010). Study on three-layer unsteady model of cuttings transport for extended-reach well. *Journal of Petroleum Science and Engineering, 73*(1-2), 171-180.

Weikey, Y., Sinha, S. L., & Dewangan, S. K. (2018). Advances in Rheological Measurement of Drilling Fluid—A Review. *Prog. Petrochem. Sci, 2*, 1-3.

Williams, C., & Bruce, G. (1951). Carrying capacity of drilling muds. *Journal of Petroleum Technology, 3*(04), 111-120.

Xiaofeng, S., Kelin, W., Tie, Y., Yang, Z., Shuai, S., & Shizhu, L. (2013). Review of hole cleaning in complex structural wells. *The Open Petroleum Engineering Journal, 6*(1).

Yang, C., Su, X., Wang, J., Cao, X., Wang, S., & Zhang, L. (2013). Facile microwave-assisted hydrothermal synthesis of varied-shaped CuO nanoparticles and their gas sensing properties. *Sensors and Actuators B: Chemical, 185*, 159-165.

Yang, L., Jiang, G., Shi, Y., Lin, X., & Yang, X. (2017). Application of ionic liquid to a high-performance calcium-resistant additive for filtration control of bentonite/water-based drilling fluids. *Journal of Materials Science, 52*(11), 6362-6375.

Zhu, X., Shen, K., Li, B., & Lv, Y. (2019). Cuttings transport using pulsed drilling fluid in the horizontal section of the slim-hole: An experimental and numerical simulation study. *Energies, 12*(20), 3939.

LIST OF PUBLICATIONS

Abbas, A. K., Alsaba, M. T., & Al Dushaishi, M. F. (2021). Improving hole cleaning in horizontal wells by using nanocomposite water-based mud. *Journal of Petroleum Science and Engineering, 203*, 108619.

Adari, R. B., Miska, S., Kuru, E., Bern, P., & Saasen, A. (2000). Selecting drilling fluid properties and flow rates for effective hole cleaning in high-angle and horizontal wells. SPE Annual Technical Conference and Exhibition,

Aftab, A., Ismail, A. R., Ibupoto, Z., Akeiber, H., & Malghani, M. (2017). Nanoparticles based drilling muds a solution to drill elevated temperature wells: A review. *Renewable and Sustainable Energy Reviews, 76*, 1301-1313.

Akpan, E. U. (2019). *Water-based drilling fluids for high temperature and dispersible shale formation applications*. University of Salford (United Kingdom).

Ali, I., Ahmad, M., & Ganat, T. (2021). Development of a new formulation for enhancing the rheological and filtration characteristics of low-solids WBMs. *Journal of Petroleum Science and Engineering, 205*, 108921.

Alther, G. (1987). The qualifications of bentonite as a soil sealant. *Engineering Geology, 23*(3-4), 177-191.

Anyanwu, C., & Mustapha Unubi, M. (2016). Experimental evaluation of particle sizing in drilling fluid to minimize filtrate losses and formation damage. SPE Nigeria Annual International Conference and Exhibition,

Apaleke, A. S., Al-Majed, A., & Hossain, M. E. (2012). Drilling fluid: state of the art and future trend. North Africa technical conference and exhibition,

Ariffin, S., & Amir, H. (2011). Water based mud lifting capacity improvement by multiwall carbon nanotubes additive. *Journal of Petroleum and Gas Engineering, 5*(2), 99-107.

Azouz, I., Shirazi, S. A., Pilehvari, A., & Azar, J. (1993). Numerical simulation of laminar flow of yield-power-law fluids in conduits of arbitrary cross-section.

Bayat, A. E., Moghanloo, P. J., Piroozian, A., & Rafati, R. (2018). Experimental investigation of rheological and filtration properties of water-based drilling fluids in presence of various nanoparticles. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 555*, 256-263.

Belavadi, M. N., & Chukwu, G. (1994). Experimental study of the parameters affecting cutting transportation in a vertical wellbore annulus. SPE Western Regional Meeting,

Bilgesu, H. I., Mishra, N., & Ameri, S. (2007). Understanding the effect of drilling parameters on hole cleaning in horizontal and deviated wellbores using computational fluid dynamics. Eastern Regional Meeting,

BOYOU, N. V. (2019). *NANOSILICA-ENHANCED WATER-BASED DRILLING MUD FOR HOLE CLEANING IN INCLINED WELLS* Universiti Teknologi Malaysia].

Boyou, N. V., Ismail, I., Hamzah, M. H., & Uche, O. M. D. (2018). Polypropylene beads in water-based mud for cuttings transportation improvement. *Chemical Engineering Transactions, 63*, 787-792.

Boyou, N. V., Ismail, I., Sulaiman, W. R. W., Haddad, A. S., Husein, N., Hui, H. T., & Nadaraja, K. (2019). Experimental investigation of hole cleaning in directional drilling by using nano-enhanced water-based drilling fluids. *Journal of Petroleum Science and Engineering, 176,* 220-231.

Brantly, J., & Carter, D. (1961). Hydraulic rotary system. *History of petroleum engineering. American Petroleum Institute, New York*, 271-452.

Briscoe, B., Luckham, P., & Ren, S. (1994). The properties of drilling muds at high pressures and high temperatures. *Philosophical Transactions of the Royal Society of London. Series A: Physical and Engineering Sciences*, *348*(1687), 179-207.

Busch, A., & Johansen, S. T. (2020). Cuttings transport: On the effect of drill pipe rotation and lateral motion on the cuttings bed. *Journal of Petroleum Science and Engineering*, *191*, 107136.

Caenn, R., Darley, H. C., & Gray, G. R. (2011). *Composition and properties of drilling and completion fluids*. Gulf professional publishing.

Cayeux, E., Mesagan, T., Tanripada, S., Zidan, M., & Fjelde, K. K. (2014). Real-time evaluation of hole-cleaning conditions with a transient cuttings-transport model. *SPE Drilling & Completion, 29*(01), 5-21.

Chesser, B., Clark, D., & Wise, W. (1994). Dynamic and static filtrate-loss techniques for monitoring filter-cake quality improves drilling-fluid performance. *SPE Drilling & Completion, 9*(03), 189-192.

Cho, H., Shah, S. N., & Osisanya, S. O. (2000). A three-segment hydraulic model for cuttings transport in horizontal and deviated wells. SPE/CIM International Conference on Horizontal Well Technology,

Cinku, K., Karakas, F., & Boylu, F. (2014). Effect of calcinated magnesite on rheology of bentonite suspensions. Magnesia-bentonite interaction. *Physicochemical Problems of Mineral Processing, 50*(2), 453--466.

Crumpton, H. (2018). *Well control for completions and interventions*. Gulf Professional Publishing.

Davoodi, S., SA, A. R., Soleimanian, A., & Jahromi, A. F. (2019). Application of a novel acrylamide copolymer containing highly hydrophobic comonomer as filtration control and rheology modifier additive in water-based drilling mud. *Journal of Petroleum Science and Engineering, 180*, 747-755.

Ebikapaye, J. (2018). Effects of temperature on the density of water based drilling mud. *Journal of Applied Sciences and Environmental Management, 22*(3), 406-408.

Egenti, N. B. (2014). Understanding drill-cuttings transportation in deviated and horizontal wells. SPE Nigeria annual international conference and exhibition,

Einstein, A. (1956). *Investigations on the Theory of the Brownian Movement*. Courier Corporation.

Elochukwu, H., Gholami, R., & Dol, S. S. (2017). An approach to improve the cuttings carrying capacity of nanosilica based muds. *Journal of Petroleum Science and Engineering, 152*, 309-316.

Epelle, E. I., & Gerogiorgis, D. I. (2017). A multiparametric CFD analysis of multiphase annular flows for oil and gas drilling applications. *Computers & Chemical Engineering, 106*, 645-661.

Esmaeili, A. (2011). Applications of nanotechnology in oil and gas industry. AIP conference proceedings,

Ford, J. T., Gao, E., Oyeneyin, M., Peden, J., Larrucia, M., & Parker, D. (1996). A new MTV computer package for hole-cleaning design and analysis. *SPE Drilling & Completion, 11*(03), 168-172.

Gautam, S., Guria, C., & Rajak, V. K. (2022). A state of the art review on the performance of high-pressure and high-temperature drilling fluids: Towards understanding the structure-property relationship of drilling fluid additives. *Journal of Petroleum Science and Engineering*, 110318.

Gbadamosi, A. O., Junin, R., Oseh, J. O., Agi, A., Yekeen, N., Abdalla, Y., Ogiriki, S. O., & Yusuff, A. S. (2018). Improving hole cleaning efficiency using nanosilica in water-based drilling mud. SPE Nigeria annual international conference and exhibition,

Guan, Z.-c., Liu, Y.-m., Liu, Y.-w., & Xu, Y.-q. (2016). Hole cleaning optimization of horizontal wells with the multi-dimensional ant colony algorithm. *Journal of Natural Gas Science and Engineering, 28*, 347-355.

Hakim, H., Katende, A., Sagala, F., Ismail, I., & Nsamba, H. (2018). Performance of polyethylene and polypropylene beads towards drill cuttings transportation in horizontal wellbore. *Journal of Petroleum Science and Engineering, 165*, 962-969.

Hall, H., Thompson, H., & Nuss, F. (1950). Ability of drilling mud to lift bit cuttings. *Journal of Petroleum Technology, 2*(02), 35-46.

Hassan, A. (2013). Review of the global oil and gas industry: a concise journey from ancient time to modern world. *Petroleum Technology Development Journal, 3*(2), 123-141.

Helms, L. (2008). Horizontal drilling. *North Dakota Department of Mineral Resources Newsletter, 35*(1), 1-3.

Heshamudin, N. S., Katende, A., Rashid, H. A., Ismail, I., Sagala, F., & Samsuri, A. (2019). Experimental investigation of the effect of drill pipe rotation on improving hole cleaning using water-based mud enriched with polypropylene beads in vertical and horizontal wellbores. *Journal of Petroleum Science and Engineering, 179*, 1173-1185.

Heydari, O., Sahraei, E., & Skalle, P. (2017). Investigating the impact of drillpipe's rotation and eccentricity on cuttings transport phenomenon in various horizontal annuluses using computational fluid dynamics (CFD). *Journal of Petroleum Science and Engineering, 156*, 801-813.

Hoelscher, K. P., Young, S., Friedheim, J., & De Stefano, G. (2013). Nanotechnology application in drilling fluids. Offshore Mediterranean Conference and Exhibition,

Iler, R. K. (1955). *The colloid chemistry of silica and silicates* (Vol. 80). LWW.

Irfan, Y. (2016). *Study of viscosity and friction factor of nano drilling fluids along with torque and drag reduction* University of Stavanger, Norway].

Islam, M. R., & Hossain, M. E. (2020). *Drilling Engineering: Towards Achieving Total Sustainability*. Gulf Professional Publishing.

Ismail, A., Hassan, Z., & Mazen, A. (2002). Drilling fluids and wellbore cleaning technology. Proceedings of the Regional Symposium of Chemical Engineering, Petaling Jaya, Malaysia,

Jain, R., Mahto, T. K., & Mahto, V. (2016). Rheological investigations of water based drilling fluid system developed using synthesized nanocomposite. *Korea-Australia Rheology Journal, 28*(1), 55-65.

Jain, R., Mahto, V., & Sharma, V. (2015). Evaluation of polyacrylamide-grafted-polyethylene glycol/silica nanocomposite as potential additive in water based drilling mud for reactive shale formation. *Journal of Natural Gas Science and Engineering, 26*, 526-537.

Javeri, S. M., Haindade, Z. W., & Jere, C. B. (2011). Mitigating loss circulation and differential sticking problems using silicon nanoparticles. SPE/IADC Middle East Drilling Technology Conference and Exhibition,

Jeevanandam, J., Barhoum, A., Chan, Y. S., Dufresne, A., & Danquah, M. K. (2018). Review on nanoparticles and nanostructured materials: history, sources, toxicity and regulations. *Beilstein journal of nanotechnology, 9*(1), 1050-1074.

Jokandan, E. F., Naeiji, P., & Varaminian, F. (2016). The synergism of the binary and ternary solutions of polyethylene glycol, polyacrylamide and Hydroxyethyl cellulose to methane hydrate kinetic inhibitor. *Journal of Natural Gas Science and Engineering, 29*, 15-20.

Kageson-Loe, N. M., Massam, J., Prebensen, O. I., Van Der Zwaag, C., Taugbol, K., & Omland, T. H. (2007). Formation-damage observations on oil-based-fluid systems weighted with treated micronized barite. European Formation Damage Conference,

Kang, H. Y., & Li, G. J. (2011). Preparation and study of polyethylene glycol (PEG)/titanium dioxide (TiO2) phase change materials. Advanced Materials Research,

Karagüzel, C., Çetinel, T., Boylu, F., Çinku, K., & Çelik, M. (2010). Activation of (Na, Ca)-bentonites with soda and MgO and their utilization as drilling mud. *Applied Clay Science, 48*(3), 398-404.

Kelessidis, V., Bandelis, G., & Li, J. (2007). Flow of dilute solid-liquid mixtures in horizontal concentric and eccentric annuli. *Journal of Canadian Petroleum Technology, 46*(05).

Khataniar, S., Chukwu, G. A., & Xu, H. (1994). Evaluation of rheological models and application to flow regime determination. *Journal of Petroleum Science and Engineering, 11*(2), 155-164.

Khatibi, M., Time, R. W., & Shaibu, R. (2018). Dynamical feature of particle dunes in Newtonian and shear-thinning flows: relevance to hole-cleaning in pipe and annulus. *International Journal of Multiphase Flow, 99*, 284-293.

Kong, M., Zhang, W., Yang, Z., Weng, S., & Chen, Z. (2011). Facile synthesis of CuO hollow nanospheres assembled by nanoparticles and their electrochemical performance. *Applied surface science, 258*(4), 1317-1321.

Larsen, T., Pilehvari, A., & Azar, J. (1997). Development of a new cuttings-transport model for high-angle wellbores including horizontal wells. *SPE Drilling & Completion, 12*(02), 129-135.

Lucky, A. P. A., & Johnson, F. A. (2018). Modification of Bingham plastic rheological model for better rheological characterization of synthetic based drilling mud. *Journal of Engineering and Applied Sciences, 13*(10), 3573-3581.

Mahmoud, H., Hamza, A., Nasser, M. S., Hussein, I. A., Ahmed, R., & Karami, H. (2020). Hole cleaning and drilling fluid sweeps in horizontal and deviated wells: Comprehensive review. *Journal of Petroleum Science and Engineering, 186*, 106748.

Mao, H., Qiu, Z., Shen, Z., & Huang, W. (2015). Hydrophobic associated polymer based silica nanoparticles composite with core–shell structure as a filtrate reducer for drilling fluid at utra-high temperature. *Journal of Petroleum Science and Engineering, 129*, 1-14.

Martins, A., Sa, C., Lourenco, A., & Campos, W. (1996). Optimizing cuttings circulation in horizontal well drilling. International Petroleum Conference and Exhibition of Mexico,

Medhi, S., Chowdhury, S., Gupta, D. K., & Mazumdar, A. (2020). An investigation on the effects of silica and copper oxide nanoparticles on rheological and fluid loss property of drilling fluids. *Journal of Petroleum Exploration and Production Technology, 10*, 91-101.

Mellott, J. (2006). Technological improvements in wells drilled with a pneumatic fluid. IADC/SPE Drilling Conference,

Mir, M. R. (2017). *Investigation of the transport mechanism of the cutting transport in drilling horizontal wells using high speed camera and PIV for analysis* University of Stavanger, Norway].

Mohamadian, N., Ghorbani, H., Wood, D. A., & Khoshmardan, M. A. (2019). A hybrid nanocomposite of poly (styrene-methyl methacrylate-acrylic acid)/clay as a novel rheology-improvement additive for drilling fluids. *Journal of Polymer Research, 26*(2), 1-14.

Mohamed, A., Salehi, S., & Ahmed, R. (2021). Significance and complications of drilling fluid rheology in geothermal drilling: A review. *Geothermics, 93,* 102066.

Mohammadsalehi, M., & Malekzadeh, N. (2011). Optimization of hole cleaning and cutting removal in vertical, deviated and horizontal wells. SPE Asia Pacific Oil and Gas Conference and Exhibition,

Naderi, M. E., Khavarpour, M., Fazaeli, R., & Ghadi, A. (2022). Improving the fluid loss and rheological characteristics of Oil-based drilling fluid by using Copper Oxide nanoparticles. *International Journal of Nano Dimension, 13*(2), 205-213.

Nazari, T., Hareland, G., & Azar, J. J. (2010). Review of cuttings transport in directional well drilling: systematic approach. SPE western regional meeting,

Ofei, T. N., & Alhemyari, S. A. (2015). Computational fluid dynamics simulation of the effect of drill pipe rotation on cuttings transport in horizontal wellbores using a Newtonian fluid. 2015 International Field Exploration and Development Conference (IFEDC 2015),

Ogunrinde, J., & Dosunmu, A. (2012). Hydraulics optimization for efficient hole cleaning in deviated and horizontal wells. Nigeria annual international conference and exhibition,

Ohenhen, I., Ogiriki, S., Imuetiyan, I., & Ezeja, O. (2018). Experimental study of temperature effect on drilling mud with local additives. International Journal of Engineering Research in Africa,

Okrajni, S. S., & Azar, J. (1986). The effects of mud rheology on annular hole cleaning in directional wells. *SPE drilling engineering, 1*(04), 297-308.

Oku, T., Motoyoshi, R., Fujimoto, K., Akiyama, T., Jeyadevan, B., & Cuya, J. (2011). Structures and photovoltaic properties of copper oxides/fullerene solar cells. *Journal of Physics and Chemistry of Solids, 72*(11), 1206-1211.

Oseh, J. O., Mohd Norddin, M., Ismail, I., Gbadamosi, A. O., Agi, A., & Ismail, A. R. (2020). 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.

Ozbayoglu, M., Sorgun, M., Saasen, A., & Svanes, K. (2010). Hole cleaning performance of light-weight drilling fluids during horizontal underbalanced drilling. *Journal of Canadian Petroleum Technology, 49*(04), 21-26.

Ozbayoglu, M. E., Saasen, A., Sorgun, M., & Svanes, K. (2008). Effect of pipe rotation on hole cleaning for water-based drilling fluids in horizontal and deviated wells. IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition,

Pang, B., Wang, S., Jiang, X., & Lu, H. (2019). Effect of orbital motion of drill pipe on the transport of non-Newtonian fluid-cuttings mixture in horizontal drilling annulus. *Journal of Petroleum Science and Engineering, 174*, 201-215.

Parizad, A., Shahbazi, K., & Tanha, A. A. (2018). Enhancement of polymeric water-based drilling fluid properties using nanoparticles. *Journal of Petroleum Science and Engineering, 170*, 813-828.

Peden, J., Ford, J., and, & Oyeneyin, M. (1990). Comprehensive experimental investigation of drilled cuttings transport in inclined wells including the effects of rotation and eccentricity. European Petroleum Conference,

Pilehvari, A. A., Azar, J., & Shirazi, S. A. (1999). State-of-the-art cuttings transport in horizontal wellbores. *SPE Drilling & Completion, 14*(03), 196-200.

Piroozian, A., Ismail, I., Yaacob, Z., Babakhani, P., & Ismail, A. S. I. (2012). Impact of drilling fluid viscosity, velocity and hole inclination on cuttings transport in horizontal and highly deviated wells. *Journal of Petroleum Exploration and Production Technology, 2*(3), 149-156.

Ponmani, S., Nagarajan, R., & Sangwai, J. S. (2016). Effect of nanofluids of CuO and ZnO in polyethylene glycol and polyvinylpyrrolidone on the thermal, electrical, and filtration-loss properties of water-based drilling fluids. *SPE Journal, 21*(02), 405-415.

Pouran, H. M. (2018). Engineered nanomaterials in the environment, their potential fate and behaviour and emerging techniques to measure them. *Handbook of environmental materials management*, 1-15.

Rafati, R., Smith, S. R., Haddad, A. S., Novara, R., & Hamidi, H. (2018). Effect of nanoparticles on the modifications of drilling fluids properties: A review of recent advances. *Journal of Petroleum Science and Engineering, 161*, 61-76.

Rahman, I. A., & Padavettan, V. (2012). Synthesis of silica nanoparticles by sol-gel: size-dependent properties, surface modification, and applications in silica-polymer nanocomposites—a review. *Journal of Nanomaterials, 2012*.

Ramsay, M., Beutier, C., McGarvey, G. B., & Hore, D. K. (2019). Adsorption of heptane–toluene binary mixtures on a hydrophobic polymer surface. *The Journal of Chemical Physics, 150*(1), 014702.

Ranjbar, R. (2010). *Cuttings transport in inclined and horizontal wellbore* University of Stavanger, Norway].

Rehm, B., Haghshenas, A., Paknejad, A., Al-Yami, A., Hughes, J., & Schubert, J. (2012). Flow drilling: underbalance drilling with liquid single-phase systems. *Underbalanced drilling: Limits and extremes*, 39-108.

Reverchon, E., & Adami, R. (2006). Nanomaterials and supercritical fluids. *The Journal of supercritical fluids, 37*(1), 1-22.

Robertson, R., & Stiff, H. (1976). An improved mathematical model for relating shear stress to shear rate in drilling fluids and cement slurries. *Society of Petroleum Engineers Journal, 16*(01), 31-36.

Rooki, R., Ardejani, F. D., Moradzadeh, A., Mirzaei, H., Kelessidis, V., Maglione, R., & Norouzi, M. (2012). Optimal determination of rheological parameters for herschel-bulkley drilling fluids using genetic algorithms (GAs). *Korea-Australia Rheology Journal, 24*(3), 163-170.

Saleh, T. A., Sarı, A., & Tuzen, M. (2016). Chitosan-modified vermiculite for As (III) adsorption from aqueous solution: equilibrium, thermodynamic and kinetic studies. *Journal of Molecular Liquids, 219*, 937-945.

Sanchez, R. A., Azar, J., Bassal, A., & Martins, A. (1997). The effect of drillpipe rotation on hole cleaning during directional well drilling. SPE/IADC drilling conference,

Sang, S., Li, W., Pu, J., & Jian, L. (2008). Novel Al2O3-based compressive seals for IT-SOFC applications. *Journal of Power Sources, 177*(1), 77-82.

Sankar, R., Manikandan, P., Malarvizhi, V., Fathima, T., Shivashangari, K. S., & Ravikumar, V. (2014). Green synthesis of colloidal copper oxide nanoparticles using Carica papaya and its application in photocatalytic dye degradation. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 121*, 746-750.

Sarafraz, M., & Hormozi, F. (2014). Scale formation and subcooled flow boiling heat transfer of CuO–water nanofluid inside the vertical annulus. *Experimental Thermal and Fluid Science, 52*, 205-214.

Schaanning, M. T., Trannum, H. C., Øxnevad, S., Carroll, J., & Bakke, T. (2008). Effects of drill cuttings on biogeochemical fluxes and macrobenthos of marine sediments. *Journal of Experimental Marine Biology and Ecology, 361*(1), 49-57.

Shadizadeh, S., & Zoveidavianpoor, M. (2012). An experimental modeling of cuttings transport for an Iranian directional and horizontal well drilling. *Petroleum science and technology, 30*(8), 786-799.

Sifferman, T., & Becker, T. (1992). Hole cleaning in full-scale inclined wellbores. *SPE drilling engineering, 7*(02), 115-120.

Smith, S. R., Rafati, R., Haddad, A. S., Cooper, A., & Hamidi, H. (2018). Application of aluminium oxide nanoparticles to enhance rheological and filtration properties of water based muds at HPHT conditions. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 537*, 361-371.

Song, X., Xu, Z., Wang, M., Li, G., Shah, S. N., & Pang, Z. (2017). Experimental study on the wellbore-cleaning efficiency of microhole-horizontal-well drilling. *SPE Journal, 22*(04), 1189-1200.

Tanaka, T., Kozako, M., Fuse, N., & Ohki, Y. (2005). Proposal of a multi-core model for polymer nanocomposite dielectrics. *IEEE transactions on dielectrics and electrical insulation, 12*(4), 669-681.

Teo, C.-H., Zhu, Y., Gao, X., Wee, A. T.-S., & Sow, C.-H. (2008). Field emission from hybrid CuO and CuCO3 nanosystems. *Solid state communications, 145*(5-6), 241-245.

Vaseem, M., Umar, A., Kim, S. H., & Hahn, Y.-B. (2008). Low-temperature synthesis of flower-shaped CuO nanostructures by solution process: formation mechanism and structural properties. *The Journal of Physical Chemistry C, 112*(15), 5729-5735.

Vert, M., Doi, Y., Hellwich, K.-H., Hess, M., Hodge, P., Kubisa, P., Rinaudo, M., & Schué, F. (2012). Terminology for biorelated polymers and applications (IUPAC Recommendations 2012). *Pure and Applied Chemistry, 84*(2), 377-410.

Vipulanandan, C., & Mohammed, A. (2014). Hyperbolic rheological model with shear stress limit for acrylamide polymer modified bentonite drilling muds. *Journal of Petroleum Science and Engineering, 122*, 38-47.

Vryzas, Z., Mahmoud, O., Nasr-El-Din, H. A., & Kelessidis, V. C. (2015). Development and testing of novel drilling fluids using Fe2O3 and SiO2 nanoparticles for enhanced drilling operations. International petroleum technology conference,

Walker, S., & Li, J. (2000). The effects of particle size, fluid rheology, and pipe eccentricity on cuttings transport. SPE/ICOTA coiled tubing roundtable,

Wang, Z.-m., & Long, Z.-h. (2010). Study on three-layer unsteady model of cuttings transport for extended-reach well. *Journal of Petroleum Science and Engineering, 73*(1-2), 171-180.

Weikey, Y., Sinha, S. L., & Dewangan, S. K. (2018). Advances in Rheological Measurement of Drilling Fluid—A Review. *Prog. Petrochem. Sci, 2*, 1-3.

Williams, C., & Bruce, G. (1951). Carrying capacity of drilling muds. *Journal of Petroleum Technology, 3*(04), 111-120.

Xiaofeng, S., Kelin, W., Tie, Y., Yang, Z., Shuai, S., & Shizhu, L. (2013). Review of hole cleaning in complex structural wells. *The Open Petroleum Engineering Journal, 6*(1).

Yang, C., Su, X., Wang, J., Cao, X., Wang, S., & Zhang, L. (2013). Facile microwave-assisted hydrothermal synthesis of varied-shaped CuO nanoparticles and their gas sensing properties. *Sensors and Actuators B: Chemical, 185*, 159-165.

Yang, L., Jiang, G., Shi, Y., Lin, X., & Yang, X. (2017). Application of ionic liquid to a high-performance calcium-resistant additive for filtration control of bentonite/water-based drilling fluids. *Journal of Materials Science, 52*(11), 6362-6375.

Zhu, X., Shen, K., Li, B., & Lv, Y. (2019). Cuttings transport using pulsed drilling fluid in the horizontal section of the slim-hole: An experimental and numerical simulation study. *Energies, 12*(20), 3939.