Journal of Petroleum Science and Engineering 179 (2019) 1173–1185

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

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

Nursyafiqah S. Heshamudin[a], Allan Katende[b,d,e,*], Halimatun A. Rashid[a], Issham Ismail[a], Farad Sagala[c], Ariffin Samsuri[a]

[a] Department of Petroleum Engineering, Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, Malaysia
[b] Department of Energy, Minerals and Petroleum Engineering. Mbarara University of Science and Technology(MUST), Uganda
[c] Department of Chemical and Petroleum Engineering, University of Calgary(UC), Canada
[d] Department of Mechanical and Industrial Engineering. Mbarara University of Science and Technology(MUST), Uganda
[e] Department of Geoscience and Petroleum, Norwegian University of Science and Technology(NTNU), Norway

ARTICLE INFO

Keywords:
Cuttings size
Cuttings transport ratio
Hole angles
Hole cleaning
Pipe rotation
Water-based mud

ABSTRACT

Field experience has shown that the inefficient transport of small cuttings is a main factor contributing to excessive drag and torque during the drilling of a deviated hole; however, very little is known about the transport behavior of small cuttings. This experimental study investigates the effect of different polypropylene bead concentrations in water-based mud (WBM) on hole cleaning, along with the effects of cutting size, drill pipe rotation, and hole inclination angle. A total of 160 runs were performed using an experimental rig consisting of a 13 ft (3.96 m) long casing with a 2 in (50.8 mm) Inner Diameter (ID) and a rotary inner pipe with a 0.8 in (20 mm) Outer Diameter (OD). Four cutting size ranges, namely, 0.5–1.0 mm, 1.0–1.4 mm, 1.4–1.7 mm, and 1.7–2.0 mm, with a density of 2400 kg/m^3 were tested in WBM with varying polypropylene bead concentrations ranging from 0 to 8 ppb. The concentric annulus flow test section was changed to vertical and horizontal angles with pipe rotation from 0 to 150 rpm. The mud density and viscosity were maintained at 10 ppg and 16 cp, respectively, under a flow velocity of 3.48 m/s (Reynolds number of 6620). The results indicate that smaller cuttings are easier to transport at all pipe rotations and polypropylene bead concentrations in both vertical and horizontal holes. The optimal pipe rotational speed was found to be 60 rpm. In this study, polypropylene beads undeniably enhanced the mud carrying capacity by significantly increasing the cutting transport ratio (CTR) by up to 16.57% in vertical holes and 15.73% in horizontal holes.

1. Introduction

ONE of the most crucial functions of mud in drilling operations is to transport the drill cuttings to the surface through the wellbore annulus. (Bird and Garrett, 1996; Boyou et al., 2019; Epelle and Gerogiorgis, 2017; Hakim et al., 2018; Kamyab and Rasouli, 2016; Majid et al., 2018; Moraveji et al., 2017; Piroozian et al., 2012; Sayindla et al., 2017; Skalle, 2010; Werner et al., 2017; Yan et al., 2018; Yeu et al., 2019; Zeng et al., 2018). Efficiently transporting cuttings is a noteworthy challenge when a long extended reach well with a horizontal section of more than twenty-five thousand feet has to be drilled. Cuttings can be ground into fine sand while being transported out of the hole, particularly when rotary drilling is used. Drilling may not be able to proceed if cutting transport remains a problem in such holes. Field experience has demonstrated that the inefficient transport of small cuttings is a main factor contributing to excessive drag and torque during extended reach drilling, where small cuttings settle at the lower part of the horizontal section. Other operational problems that may surface are; stuck pipe, reduced rate of penetration (ROP), etc (Akhshik et al., 2016; Amanna et al., 2016; Beck et al., 1947; Becker and Azar, 1985; Bilgesu et al., 2007; Bland et al., 2006; Clark and Bickham, 1994; Duan et al., 2008b; Egenti, 2014; Epelle and Gerogiorgis, 2018a,b,c; Ezeakacha and Salehi, 2019; Hussaini and Azar, 1974; Luo et al., 1994; Mohammadzadeh et al., 2016; Ozbayoglu et al., 2010a; Pigott, 1941; Saxena et al., 2017; Sifferman et al., 1974; Walker and Li, 2000; Yu et al., 2004).

Yu et al. (2004) observed that under the action of gravity, cuttings have a tendency to settle outside the drilling fluid, which is commonly

* Corresponding author. Department of Energy, Minerals and Petroleum Engineering. Mbarara University of Science and Technology(MUST), Uganda.
E-mail addresses: allan_katende@hotmail.com, akatende@must.ac.ug, allank@alumni.ntnu.no (A. Katende), issham@petroleum.utm.my (I. Ismail).

https://doi.org/10.1016/j.petrol.2019.04.086
Received 15 January 2019; Received in revised form 23 April 2019; Accepted 24 April 2019
Available online 02 May 2019
0920-4105/ © 2019 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/BY-NC-ND/4.0/).

known as slip velocity. The slip velocity is dependent on the density and viscosity of the drilling fluid. The hole angle, annular velocity and viscosity of the drilling fluid are considered to be the most critical parameters in effective hole cleaning. The drill cuttings (solid particles) that must be circulated from the bottom of the hole to the surface have four forces acting on them: a downward gravitational force, an upward buoyant force due to the cuttings being soaked up in the drilling fluid, a drag force parallel to the direction of the mud flow due to the mud flowing around the cutting particles and a lift force perpendicular to the direction of the mud flow, which is also due to the mud flowing around the cutting particles.

Iyoho and Azar (1981) presented an accurate slot-flow model for non-Newtonian fluid flow through eccentric annuli. Their analysis examined the factors affecting the transport of cuttings in directional wells, such as drilling fluid velocity, inclination angle, drilling fluid viscosity and rate of penetration (ROP). They also determined that designing the mud flow for transporting cuttings based on the nominal average velocity could lead to serious problems associated with the buildup of cuttings in the low-velocity region of the annulus.

Ford et al. (1990) observed two distinctly different mechanisms of cutting transport, namely, the transport of cuttings up the annulus by rolling or sliding along the low side wall and the transport of cuttings in suspension in the flowing annular fluid. These two mechanisms resulted in the definition of two critical fluid velocities, both of which satisfy the minimum transport velocity (MTV). One is the fluid velocity needed to initiate and maintain a rolling or sliding motion of the cuttings along the low side wall of the annulus while maintaining the MTV for cutting rolling or sliding. The other is the higher fluid velocity that maintains the cuttings in suspension in the circulating fluid and the MTV for suspended cuttings. The point at which all of the cuttings are transported up the annulus may be visually observed in the 'test section' of the column. At this point, the circulating fluid flow rate is measured, and the annular fluid velocity (MTV) can subsequently be determined.

Azar and Sanchez (1997) presented a comprehensive review of the factors that affect cutting transport, listing flow rate, hole inclination angle, annular eccentricity, drill string rotation and ROP as the most prevalent parameters.

Larsen et al. (1997) confirmed the results of Iyoho and Azar (1981) by concluding that the inclination angle and drilling fluid flow rate had the most significant effects on hole cleaning. The parameters listed by Iyoho and Azar (1981) impose some limitations on the system. Under the most desirable conditions, the drilling operation is run within the allowable multidimensional area of these parameters. Internal states, outputs and inputs need to be monitored to ensure safe windows of operation.

According to Nazari et al. (2010), finding a solution for removing drill cuttings from the annulus can be addressed by finding relationships between drilling parameters such as ROP, eccentricity, pressures, torque, drag, WOB, etc. The parameters should be classified as effective parameters or affected parameters, in which any change in the effective parameters will cause a change in the affected parameters. The affected parameters are further classified into two groups, namely, internal states and outputs. The outputs are measured parameters, whereas internal states cannot be measured during drilling.

Ozbayoglu et al. (2010b) found that there is a linear relationship between the flow rate and transport velocity of cuttings. Cuttings will start to accumulate at the bottom of the pipe and create a stationary cuttings bed when the total volumetric flow rate does not generate the fluid velocities required for transporting the cuttings.

In a typical bed erosion test conducted by Adari et al. (2000), the bed height decreased exponentially to a certain residual bed level, or it decreased to zero, depending on the drilling mud properties and mud flow rate. Duan et al. (2008b) found that the bed height decreases almost linearly with an increasing flow rate within the range of 200–400 rpm and that the concentration of cuttings is reduced by 10–15%, regardless of pipe rotation speed, testing fluid or cutting size.

Mohammadsalehi and Malekzadeh (2011) noted that drilling fluid rheology and flow rate are the two main parameters that strongly influence cutting transport, but controlling these parameters in the field is relatively easy. Ogunrinde and Dosunmu (2012) also stated that fluid flow rate is the dominating parameter affecting the development of the cutting bed.

It has been well documented that as the hole angle increases from zero to approximately 65° from the vertical, hole cleaning becomes increasingly difficult and the hydraulic requirement increases. Azar and Sanchez (1997) reported that the flow rate requirements peak at hole angles between 65° and 75° from the vertical, and Adari et al. (2000) also reported that the circulation time increases in the case of high-angle wells.

Cho et al. (2002) classified hole inclination into three sections, namely, a vertical and near-vertical section (0° to 30° from the vertical), a horizontal to near-horizontal section (60° to 90° deviation), and a transit section (30° to 60° deviation), in the development of their model. It was shown that the wellbore deviation has significant effects on cutting transport. The cutting bed nearly vanished at 25° to 30°, and it was reported that there is no bed at 0° to 25°. In the transit segment, the cutting bed abruptly decreases with a decrease in hole inclination angle. However, the stationary bed in the horizontal segment is nearly constant or slightly increases, which was explained in the experimental study on small cutting transport by Duan et al. (2008b), in which the hole angle had only minor effects on cutting concentration and bed height within the range of 70° to 90° from the vertical.

Williams and Bruce (1951) observed that the carrying capacity is higher when there is pipe rotation in the drilling process. The centrifugal forces established by the pipe increase the carrying capacity because they tend to project the particles away from the pipe into regions of higher velocity, thus preventing small and medium particles from slipping down the wall of the centre pipe. The effectiveness of drill pipe rotation in increasing carrying capacity is caused in part by the fact that it aids in creating turbulence and in part by the fact that it helps prevent the existence of stagnant, gelled pockets between the drill pipe and the wall of the bore hole.

Azar and Sanchez (1997) also demonstrated that pipe rotation caused by the different modes of vibrations (torsional, longitudinal, and lateral) has moderate to significant effects on cutting transport efficiency in directional wells. The level of enhancement in removing drill cuttings due to pipe rotation is a function of the combination of mud rheology, cutting size, flow rate, and the dynamic behavior of the string.

Sanchez et al. (1999) reported that the dynamic behavior of the drill pipe, including steady-state vibration, unsteady-state vibration, whirling rotation and true axial rotation parallel to the hole axis, plays a major role in determining the magnitude of the improvement in hole cleaning. The authors found that only orbital motion improves hole cleaning. Orbital motion of the pipe improves the transport of cuttings in two ways: by mechanical agitation of cuttings in an inclined hole in which resting cuttings on the lower side of hole are swept into the upper side, provided that the annular velocity is higher, and by exposing cuttings under the drill string to the moving fluid particles.

However, the drill pipe is generally not concentric with the hole, particularly in cases of directional drilling when the pipe's weight causes a strong tendency for the pipe to lie against the hole. Gravity shifts cuttings to the lowest side of the hole, building a bed of small rock chips on the lower side of the hole known as the cutting bed. This effect can lead to significant problems for the drilling operation if the pipe becomes stuck. For applications of directional drilling, Iyoho and Azar (1981) defined positive and negative eccentricities as pipe displacement toward the low side and high side of the hole, respectively. The limited study conducted by Thomas et al. (1982) on a vertical wellbore found that no definite trend has been established regarding the effect of eccentricity on particle concentration, but the effect appears to be oscillatory in nature.

Studies by Tomren et al. (1986) revealed that in directional drilling, hole eccentricity produced some effects on bed thickness and particle concentration. The concentration of cuttings is the lowest when the pipe is concentric with the hole, which indicates good hole cleaning. The worst cutting transport was observed in cases of both negative and positive eccentricity, defined as hole inclination angles less than 35° and greater than 55°, respectively. The effect of eccentricity was not consistent between the transition zones of 35° to 55°. The rate of bed buildup appeared to be slightly higher in the positive-eccentricity case.

The findings of Ford et al. (1990) contradict those reported by Tomren et al. (1986), as negative- and positive-eccentricity annuli were observed to yield better borehole cleaning than concentric annuli. Azar and Sanchez (1997) argued that positive eccentricity is the worst position for cutting transport. Positive eccentricity causes very low fluid velocities in the narrow gap below the drill string, where most of the cuttings are located, whereas higher fluid velocities occur in the wider gap above the drill string.

Hakim et al. (2018) proposed a method for improving hole cleaning in a horizontal wellbore with the aid of polyethylene and polypropylene beads. The authors used a mud formulation reported by Scomi (2018) to observe the effect of polymer beads on cutting transport efficiency. The analysis demonstrated that polymer beads can improve cutting transport efficiency. The experiments were conducted with the absence of pipe rotation.

Yi et al. (2017) and Yeu et al. (2019) performed experiments to improve hole cleaning using low-density polyethylene (LDPE) beads and high-density polyethylene (HDPE) beads at different hole angles. Their experiments used a mud formulation reported by Scomi (2018) without commercial viscosifiers to investigate the effect of polymer beads on cutting transport efficiency. Experimental results indicated that both LDPE and HDPE beads can improve hole cleaning efficiency better than basic mud can. However, LDPE beads performed better than HDPE beads; moreover, both studies were also carried out in the absence of pipe rotation.

Table 1 presents a summary of the previous studies that have investigated the effect of pipe rotation on hole cleaning. Based on these studies, the following questions can be asked. Why and under what conditions are drill cuttings harder or easier to transport especially in a horizontal hole as compared to a vertical hole? How will the addition of polypropylene beads improve the carrying capacity of mud? To what extent does the effect of pipe rotation improve hole cleaning? Does pipe rotation behavior show any variations as the bead concentration is changed? These questions form the basis of this study to elucidate the effect of pipe rotation on hole cleaning. The reason is that polypropylene beads provide a buoyancy force, which can impart an additional lifting capacity in the form of collision and drag in the drilling fluid due to its less dense nature, aiding in lifting cuttings in a considerably more efficient manner from the wellbore to the surface.

2. Experimental setup and methods

The purpose of this study was to investigate the effect of pipe rotation on cutting lifting efficiency using different concentrations of polypropylene beads and different cutting sizes in WBM for vertical and horizontal wellbores.

2.1. Test matrix

2.1.1. Simulated drill cuttings

Fine sands were used as solid particles or simulated drill cuttings for this study. The cuttings had irregular shapes with a density of 2.4 g/cc (2400 kg/m^3), as determined using the ASTM D4253-00 (2006) ASTM (2006) testing method. The collected sand was washed and dried at 80^{o}C using an oven (see Fig. 1).

To prepare the sand samples, the sand particles were washed, cleaned and dried in a typical laboratory oven, as shown in Figure LABEL:fig:oven. Then, the sieve shaker shown in Figure LABEL:fig:shaker was used to sieve the sand samples to obtain the desired sizes. Four size ranges of sand-sized cuttings, shown in Table 2, namely, 0.5–1.0 mm, 1.0–1.4 mm 1.4–1.7 mm, and 1.7–2.0 mm, were obtained by using a sieve shaker, as shown in Figure LABEL:fig:shaker.

2.1.2. Polypropylene beads

Fig. 2 shows the polypropylene beads used in this study. The polypropylene beads had a regular size of 4.0 mm and were spherical in shape with a density of 0.9 g/cc (900 kg/m^3). Polypropylene beads have a melting point temperature above 130^{o}C (266^{o}F), which enables polypropylene polymers to be widely used in drilling operations.

Polypropylene beads were selected in this study due to their lower density compared with that of cuttings and drilling mud, which provides the intended buoyancy force to improve the transport of cuttings. The polymer beads used are generally inert and therefore do not react with drilling mud; thus, the beads can be reused in the system. Polypropylene in particular may provide an economic and cost-effective solution. Table 3 shows the properties of polypropylene beads.

Table 1
Summary of previous studies investigating the effect of drill–pipe rotation on hole cleaning.

Authors	Approach	Remarks
Pang et al. (2018, 2019)	CFD	The drill pipe rotation produces a spiral flow, whereas orbital motion of the drill pipe improves cutting transport but increases both the resistance and resultant moment exerted by the liquid-solid mixture.
Ytrehus et al. (2018)	Experimental	Cutting transport in the absence of drill pipe rotation is significantly better when the well angle is less than the critical angle.
Moraveji et al. (2017)	CFD	Drill pipe rotation affects hole cleaning when the inclination is increased
Epelle and Gerogiorgis (2017)	CFD	Pipe rotation accompanied by a slight pressure increase improves hole cleaning.
Heydari et al. (2017)	CFD	Pipe rotation effect is negligible at certain speeds of rotation and may increase cuttings' accumulation due to eccentricity
Akhshik et al. (2015)	CFD-DEM	When a critical speed at high fluid inlet velocities is attained, the contribution of drill pipe rotation vanishes.
Sun et al. (2014)	CFD	When flow rates are low or intermediate, pipe rotation has a significant on annular cutting volume and pressure drop.
Rooki et al. (2018)	CFD	Hole cleaning ratio increases with annular velocity, foam quality,& drill pipe rotation
Terry and Ravi (2010)	Mathematical Modeling	Drill pipe rotation may have a significant effect on shear rates and fluid viscosities across the annular gap.
Ozbayoglu et al. (2008)	Experimental & Modeling	The effect of pipe rotation on cuttings transport increases with fluid viscosity.
Bilgesu et al. (2007)	CFD	Drill pipe rotation enhances hole cleaning, but its effect is greater on smaller particles.
Sanchez et al. (1999)	Experimental	The effect of drill pipe rotation on hole cleaning is a function of the compound effect of mud rheology, cutting size, and mud flow rate.
Peden et al. (1990)	Experimental and Numerical	The use of high-viscosity fluids combined with pipe rotation appears to enhance the hole cleaning greatly, especially at highly deviated angles.

Table 2
Properties of cuttings.

Cutting Size (mm)	Drag	Slip Velocity	Drag Force
	Coefficient, $C_d(-)$	(m/s)	10^{-6} (N)
0.5–1.0	14.83	0.026	2.59
1.0–1.4	8.09	0.044	10.69
1.4–1.7	5.82	0.059	22.96
1.7–2.0	4.63	0.072	39.04



(a) Laboratory Oven (b) Sieve Shaker.

Fig. 1. Laboratory equipment used in the preparation of sand cuttings.



Fig. 2. Polypropylene beads.

Table 3
Polypropylene beads chemical properties.

Properties	TITANPRO	ASTM
	SM 840	Method
Density, g/cm^3	0.9	D1505
Tensile strength at yield, kg/cm^2	280	D638
Elongation at yield, %	10	D638
Rockwell hardness, R scale	80	D785A
Water absorption after 24 h, %	0.02	D570

2.2. Drilling mud preparation

API (2009) recommended practices were followed in the preparation of the WBM used in this experimental study. The WBM used in this work is a mixture of bentonite as the viscosifier, barite as the weighting agent, xanthan gum and polypac-R as the thickener, and water as the continuous phase. The rheological properties were measured and maintained constant throughout the experiment to establish a justified basis for evaluating the transport of cuttings between WBM and WBM with various concentrations of polypropylene. Four concentrations of polypropylene beads, namely, 2, 4, 6, and 8 ppb, were applied. Table 4 and Table 5 show the components of the drilling mud used in the study.

Polypropylene reduced the density of the drilling mud because it is less dense than water. Hence, the proportion of barite required increased as the concentration of polypropylene increased to maintain the density and rheological properties of the drilling mud. The addition of barite successfully kept the mud density constant at 10 ppg in all experiments.

Table 4
Drilling mud composition.

Mud type	Composition		
	Bentonite (g)	Barite (g)	Polypropylene (g)
Water-based mud (WBM)	4285.71	39840	857.14
WBM with 2 ppb polypropylene	4285.71	39334.3	1714.29
WBM with 4 ppb polypropylene	4285.71	40088.6	2571.43
WBM with 6 ppb polypropylene	4285.71	40092.9	3428.57
WBM with 8 ppb polypropylene	4285.71	40594.3	4285.71

Table 5
Rheological properties of water-based mud used with various concentrations of polypropylene beads.

	WBM	WBM & 2 ppb PP	WBM & 4 ppb PP	WBM & 6 ppb PP	WBM & 8 ppb PP
ρ, ppg	10	10	10	10	10
μ_a, cp	48	48	48	48	48
μ_p, cp	16	16	16	16	16
Y_p, lb/100 ft^2	16	16	16	16	16
Gel strength, 10 s–10 min	5–6	5–6	5–6	5–6	5–6
Filtrate liquid, ml	4	4.5	5.1	5.6	5.9
Mud cake thickness, /32 in	2	2.23	2.55	2.86	3.06

2.3. Specification of experimental variables

The test matrix in section 2.1 was designed to study the effects of cutting size, optimum drill pipe rotation, and hole inclination angle on the cutting transport ratio (CTR). The CTR is defined as the final weight of transported cuttings divided by the initial weight of the cuttings.

$$CTR(\%) = \frac{Final\ \ dried\ \ weight\ \ of\ \ transported\ \ cuttings}{Initial\ \ dried\ \ weight\ \ of\ \ cuttings} \times 100 \quad (1)$$

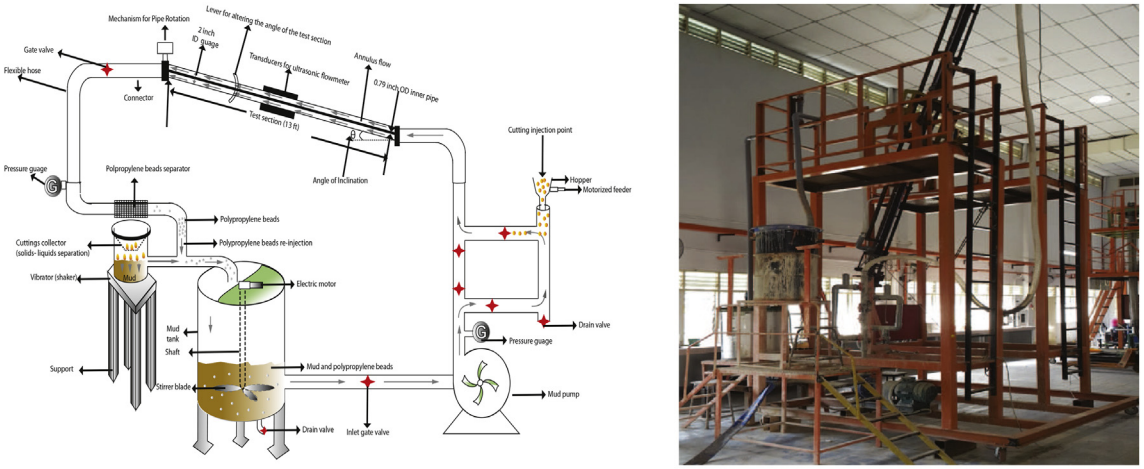
Varying concentrations of polypropylene were injected into the drilling fluid to perform a comparative study to evaluate the enhancement in the CTR. The CTR is an important hole cleaning indicator that reflects general cleaning status because it represents the success rate of cutting transport in a well.

2.4. Lab-scale flow-loop rig simulator

A lab-scale flow-loop rig simulator (Fig. 3) was used to investigate the effect of pipe rotation using polypropylene beads in WBM in vertical and horizontal wellbores.

2.5. Experimental procedure

The drilling mud was prepared in two separate phases to avoid coagulation of the drilling mud. In the first phase, a mixture of xanthan gum, polypac-R, caustic soda and 50 L of water was prepared using a laboratory stirrer. The second phase involved a mixture of bentonite, barite and 100 L of water prepared inside the mud tank shown in Fig. 3. Bentonite and barite were stirred using a six-blade stirrer until the mixture was stabilized, and the mixture from the first stage was then added. Weighed polypropylene beads were subsequently added to the



(a) Schematic of the flow-loop rig simulator

(b) Layout of the flow-loop rig simulator.

Fig. 3. Flow-loop rig simulator.

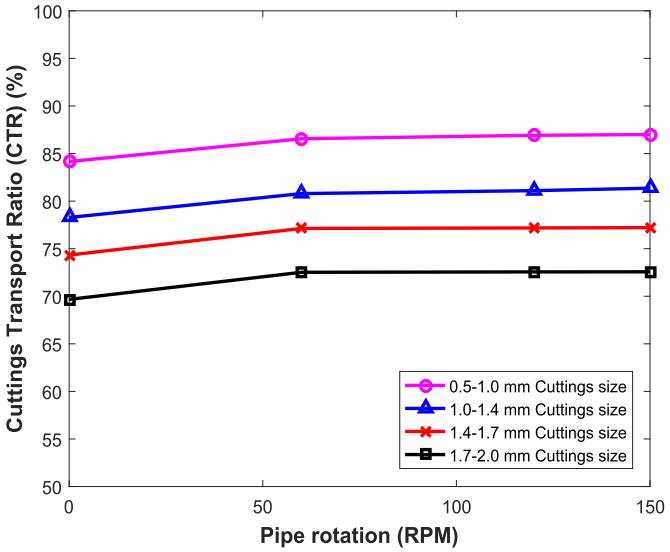


Fig. 4. CTR vs. pipe rotation for different cutting sizes in vertical hole for WBM.

mixture. The experiment was conducted at ambient temperature, 25°C, and pressure, 101.325 kPa, throughout the process.

The rig simulator was preset to the desired hole angle and pipe rotation. A total of 160 test runs were conducted to cover the scope of this experimental study. A typical run process consisted of the following five experimental stages.

In the first stage, drilling mud was pumped into the annular test section from the mud tank. The mud circulated continuously for 10 min to ensure a stabilized flow. The mud flow rate was kept constant throughout the run at 0.16 ft^3/s by using an ultrasonic flowmeter.

In the second stage, once the flow rate was stabilized, weighed cuttings were injected into the test section from the cutting feed hopper. The flow of drilling mud was diverted to the bypass line to carry the cuttings and to simulate the drilling process that was initiated.

In the third stage, drilling mud carrying cuttings that flowed through the test section and back to the mud tank was observed. The time at which the mud flow was diverted through the bypass line to the cutting separation system, which is a double-stage wire mesh separator, was recorded. The flow loop from the test section to the mud tank was shut by closing the valve. Cuttings were collected at the wire mesh, and the separated mud circulated back to the mud tank. The time was recorded, and after 7 min of flow, the drilling mud was diverted back to the mud tank by closing the bypass valve. Cuttings and polypropylene recovered at the wire mesh were collected for further processing.

In the fourth stage, cuttings and polypropylene beads collected at the screener were separated using tap water. Reusable polypropylene beads were reinjected back into the system. The collected cuttings were dried, weighed and recorded.

Finally, drill mud was flushed in the test section to the mud tank. The test section was clear of cuttings. The weighed cuttings were re-injected for the next run. The estimated time required to a complete a run was approximately 20 min. To obtain a data point, three test runs were performed prior to taking/calculating an average value to ensure consistency. The experiment was repeated by varying the pipe rotation, concentration of polypropylene, hole angle and cutting size.

3. Results and discussion

3.1. Effects of drill pipe rotation

Drill pipe rotation helps to increase the CTR for all cutting sizes with increasing number of rotations. However, the extent to which the pipe rotation helps to increase cutting transport depends on the cutting size and hole angle. In this study, the effects of pipe rotational speeds of 0, 60, 120 and 150 rpm for all cutting size ranges, namely, 0.5–1.0 mm, 1.0–1.4 mm, 1.4–1.7 mm, and 1.7–2.0 mm, were tested. Industrial rotational speeds are in the range of 60–180 rpm.

Fig. 4 shows CTR vs. pipe rotation for four different cutting sizes in a vertical hole for WBM. The CTR increases for 0.5–1.0 mm, 1.0–1.4 mm, 1.4–1.7 mm, and 1.7–2.0 mm cuttings when the drill pipe rotational speed increases from 0 to 150 rpm are 2.39%, 2.51%, 2.80%, and 2.85%, respectively (absolute difference obtained by directly subtracting two ratios). The highest CTR increase occurs when the pipe rotational speed is increased from 0 to 60 rpm, with the CTR increasing within 2.41–4.23%, depending on the cutting size. The CTR increases from 60 to 120 rpm and from 120 to 150 rpm were minimal and almost negligible, within 0.04–0.36% and 0.01–0.26%, respectively.

Fig. 5 shows CTR vs. pipe rotation for four different cutting sizes in a vertical hole for WBM with 2 ppb polypropylene beads. The CTR increases for 0.5–1.0 mm, 1.0–1.4 mm, 1.4–1.7 mm, and 1.7–2.0 mm cuttings when the drill pipe rotational speed increases from 0 to 150 rpm are 2.80%, 2.89%, 3.24%, and 4.81%, respectively. The highest CTR increase occurs when the pipe rotational speed is increased from 0 to 60 rpm, with the CTR increase within 2.14–4.12%, depending on the cutting size. The CTR increases from 60 to 120 rpm and from 120 to 150 rpm were minimal and almost negligible, within 0.03–0.57% and 0.09–0.19%, respectively.

Fig. 6 shows CTR vs. pipe rotation for four different cutting sizes in a

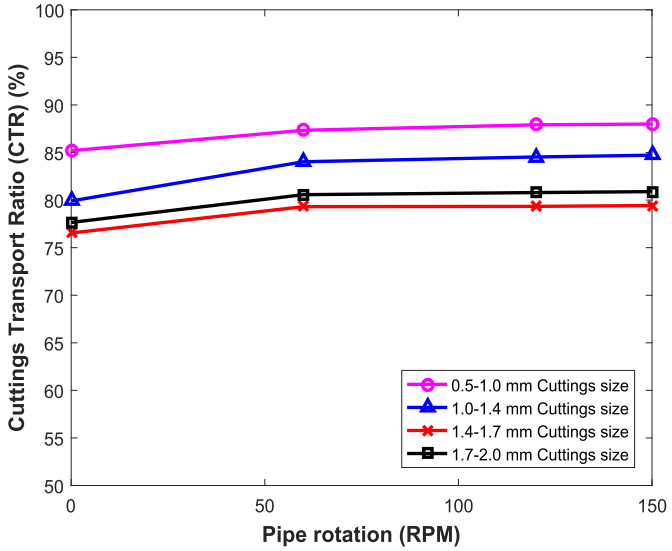


Fig. 5. CTR vs. pipe rotation for different cutting sizes in vertical hole for WBM and 2 ppb polypropylene beads.

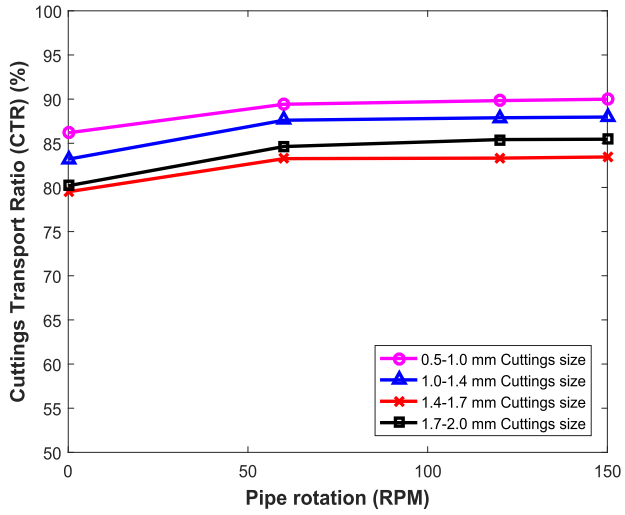


Fig. 6. CTR vs. pipe rotation for different cutting sizes in vertical hole for WBM and 4 ppb polypropylene beads.

vertical hole for WBM with 4 ppb polypropylene beads. The CTR increases for 0.5–1.0 mm, 1.0–1.4 mm, 1.4–1.7 mm, and 1.7–2.0 mm cuttings when the drill pipe rotational speed increases from 0 to 150 rpm are 3.81%, 4.77%, 4.94%, and 5.27%, respectively. The highest CTR increase occurs when the pipe rotational speed is increased from 0 to 60 rpm, with the CTR increase within 3.23–4.75%, depending on the cutting size. The CTR increases from 60 to 120 rpm and from 120 to 150 rpm were minimal and almost negligible, within 0.06–0.56% and 0.04–0.16%, respectively.

Fig. 7 shows CTR vs. pipe rotation for four different cutting sizes in a vertical hole for WBM with 6 ppb polypropylene beads. The CTR increases for 0.5–1.0 mm, 1.0–1.4 mm, 1.4–1.7 mm, and 1.7–2.0 mm cuttings when the drill pipe rotational speed increases from 0 to 150 rpm are 3.61%, 4.78%, 4.92%, and 5.10%, respectively. The highest CTR increase occurs when the pipe rotational speed is increased from 0 to 60 rpm, with the CTR increase within 2.72–4.56%, depending on the cutting size. The CTR increases from 60 to 120 rpm and from 120 to 150 rpm were minimal and almost negligible, within 0.09–0.64% and 0.02–0.31%, respectively.

Fig. 8 shows CTR vs. pipe rotation for four different cutting sizes in a

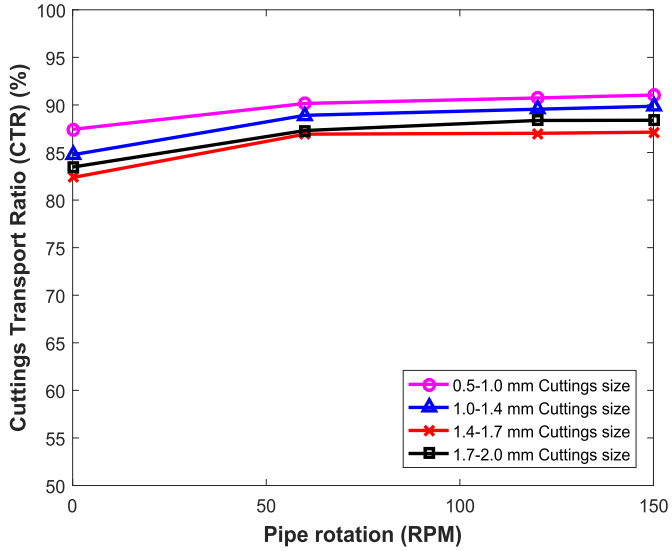


Fig. 7. CTR vs. pipe rotation for different cutting sizes in vertical hole for WBM and 6 ppb polypropylene beads.

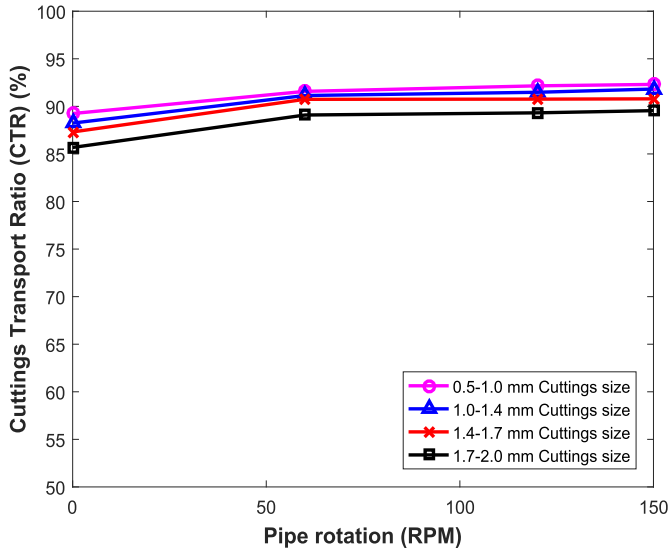


Fig. 8. CTR vs. pipe rotation for different cutting sizes in vertical hole for WBM and 8 ppb polypropylene beads.

vertical hole for WBM with 8 ppb polypropylene beads. The CTR increases for 0.5–1.0 mm, 1.0–1.4 mm, 1.4–1.7 mm, and 1.7–2.0 mm cuttings when the drill pipe rotational speed increases from 0 to 150 rpm are 3.06%, 3.48%, 3.58%, and 3.87%, respectively. The highest CTR increase occurs when the pipe rotational speed is increased from 0 to 60 rpm, with the CTR increase within 2.33–3.43%, depending on the cutting size. The CTR increases from 60 to 120 rpm and from 120 to 150 rpm were minimal and almost negligible, within 0.02–0.58 and 0.03–0.34%, respectively.

Fig. 9 shows CTR vs. pipe rotation for four different cutting sizes in a horizontal hole for WBM. The CTR increases for 0.5–1.0 mm, 1.0–1.4 mm, 1.4–1.7 mm, and 1.7–2.0 mm cuttings when the drill pipe rotational speed increases from 0 to 150 rpm are 5.10%, 6.43%, 6.44%, and 7.22%, respectively. The highest CTR increase occurs when the pipe rotational speed is increased from 0 to 60 rpm, with the CTR increase within 4.99–6.81%, depending on the cutting size. The CTR increases from 60 to 120 rpm and from 120 to 150 rpm were minimal and almost negligible, within 0.03–0.34% and 0.04–0.09%, respectively.

Fig. 10 shows CTR vs. pipe rotation for four different cutting sizes in

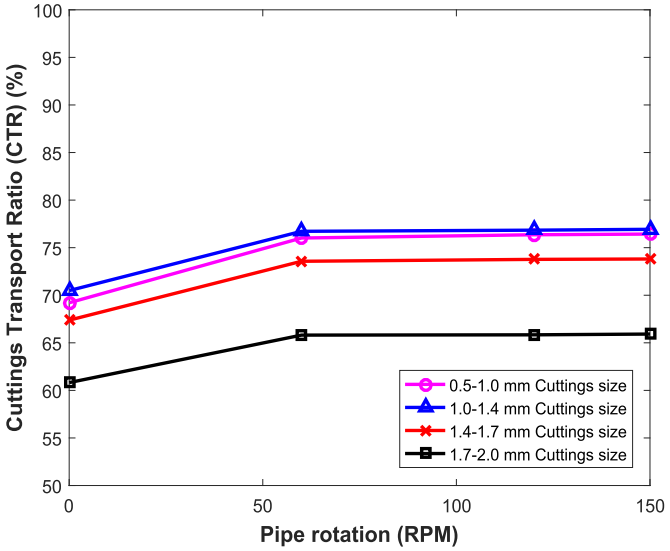


Fig. 9. CTR vs. pipe rotation for different cutting sizes in horizontal hole for WBM.

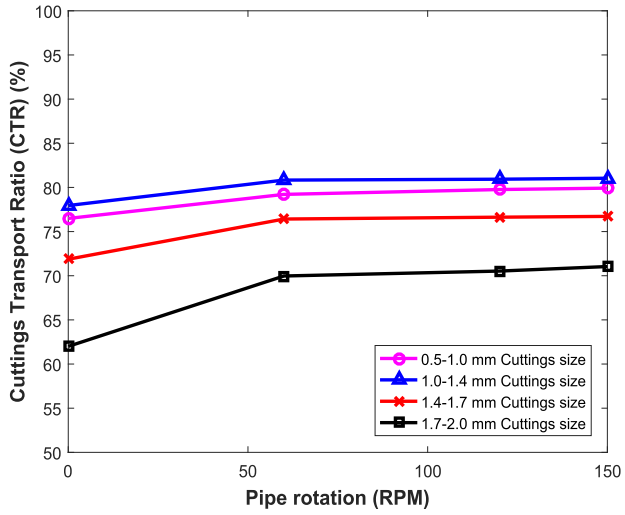


Fig. 10. CTR vs. pipe rotation for different cutting sizes in horizontal hole for WBM and 2 ppb polypropylene beads.

a horizontal hole for WBM with 2 ppb polypropylene beads. The CTR increases for 0.5–1.0 mm, 1.0–1.4 mm, 1.4–1.7 mm, and 1.7–2.0 mm cuttings when the drill pipe rotational speed increases from 0 to 150 rpm are 3.19%, 3.43%, 4.85%, and 8.83%, respectively. The highest CTR increase occurs when the pipe rotational speed is increased from 0 to 60 rpm, with the CTR increase within 2.72–7.97%, depending on the cutting size. The CTR increases from 60 to 120 rpm and from 120 to 150 rpm were minimal and almost negligible, within 0.10–0.56 and 0.09–0.21%, respectively.

Fig. 11 shows CTR vs. pipe rotation for four different cutting sizes in a horizontal hole for WBM with 4 ppb polypropylene beads. The CTR increases for 0.5–1.0 mm, 1.0–1.4 mm, 1.4–1.7 mm, and 1.7–2.0 mm cuttings when the drill pipe rotational speed increases from 0 to 150 rpm are 3.86%, 4.06%, 6.65%, and 6.81%, respectively. The highest CTR increase occurs when the pipe rotational speed is increased from 0 to 60 rpm, with the CTR increase within 3.40–6.70%, depending on the cutting size. The CTR increases from 60 to 120 rpm and from 120 to 150 rpm were minimal and almost negligible, within 0.02–0.37 and 0.09–0.25%, respectively.

Fig. 12 shows CTR vs. pipe rotation for four different cutting sizes in

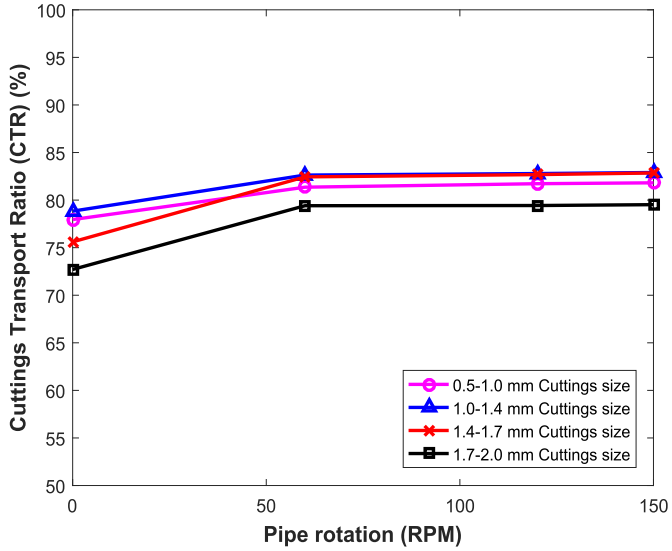


Fig. 11. CTR vs. pipe rotation for different cutting sizes in horizontal hole for WBM and 4 ppb polypropylene beads.

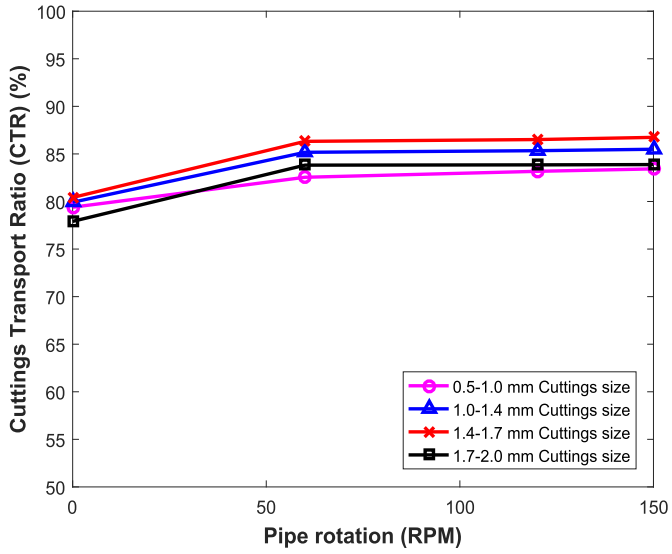


Fig. 12. CTR vs. pipe rotation for different cutting sizes in horizontal hole for WBM and 6 ppb polypropylene beads.

a horizontal hole for WBM with 6 ppb polypropylene beads. The CTR increases for 0.5–1.0 mm, 1.0–1.4 mm, 1.4–1.7 mm, and 1.7–2.0 mm cuttings when the drill pipe rotational speed increases from 0 to 150 rpm are 4.65%, 5.57%, 5.97%, and 6.32%, respectively. The highest CTR increase occurs when the pipe rotational speed is increased from 0 to 60 rpm, with the CTR increase within 3.73–5.91%, depending on the cutting size. The CTR increase from 60 to 120 rpm and from 120 to 150 rpm was minimal and almost negligible, within 0.03–0.37% and 0.03–0.23%, respectively.

Fig. 13 shows CTR vs. pipe rotation for four different cutting sizes in a horizontal hole for WBM with 8 ppb polypropylene beads. The CTR increases for 0.5–1.0 mm, 1.0–1.4 mm, 1.4–1.7 mm, and 1.7–2.0 mm cuttings when the drill pipe rotational speed increases from 0 to 150 rpm are 4.42%, 4.48%, 4.86%, and 4.99%, respectively. The highest CTR increase occurs when the pipe rotational speed is increased from 0 to 60 rpm, with the CTR increase within 3.94–4.82%, depending on the cutting size. The CTR increases from 60 to 120 rpm and from 120 to 150 rpm were minimal and almost negligible, within 0.03–0.73 and 0.01–0.25%, respectively.

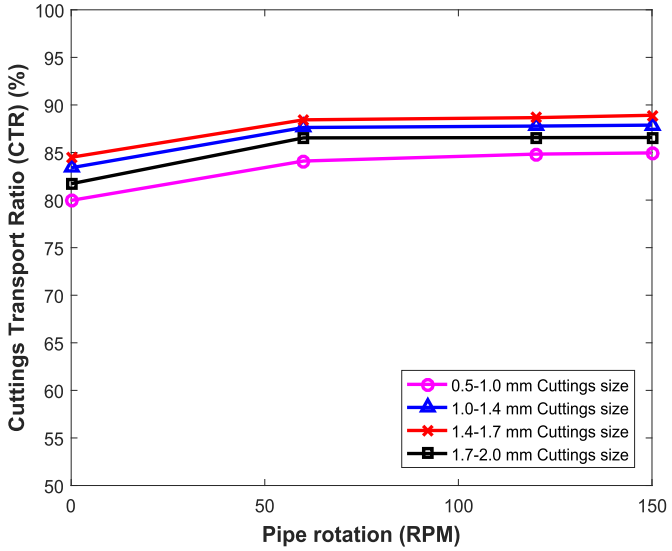


Fig. 13. CTR vs. pipe rotation for different cutting sizes in horizontal hole for WBM and 8 ppb polypropylene beads.

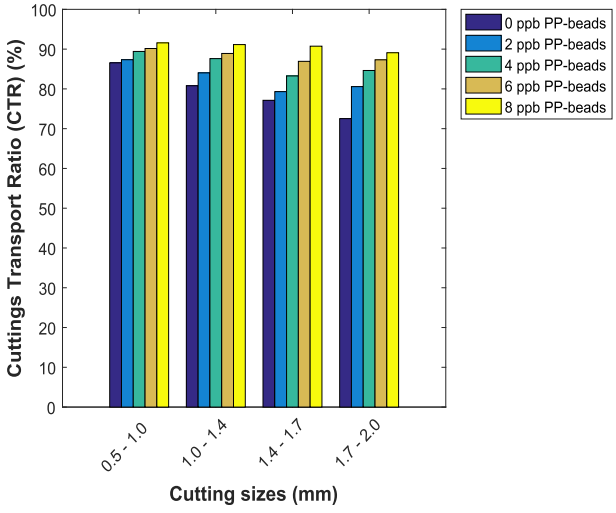


Fig. 14. Cutting sizes in vertical hole with a pipe rotational speed of 60 rpm.

As shown in Figs. 4–13, the CTR values for all cutting sizes increase as the rotational speed increases from 0 to 60 rpm, regardless of the polypropylene concentration and hole angle. In a vertical hole, as the drill pipe rotational speed increases from 0 to 60 rpm, the CTR increases for 0.5–1.0 mm are within 2.14–3.23%, those for 1.0–1.4 mm are within 2.24–4.31 those for 1.4–1.7 mm are within 2.46–4.41% and those for 1.7–2.0 mm are within 2.90–4.75%. In a horizontal hole, as the drill pipe rotational speed increases from 0 to 60 rpm, the CTR increases for 0.5–1.0 mm are within 2.72–6.23%, those for 1.0–1.4 mm are within 2.88–6.70%, those for 1.4–1.7 mm are within 3.73–6.81% and those for 1.7–2.0 mm are within 4.55–7.97%.

Moreover, the increasing trend of the CTR for both vertical and horizontal holes increases as the cutting size increases with increasing pipe rotation. This result indicates that a larger cutting size provides a better CTR improvement due to pipe rotation. The CTR improvement due to pipe rotation in the horizontal hole has a better cutting lifting effect than that in the vertical annulus does. This finding can be interpreted as the gradient of the CTR at the horizontal between 0 and 60 rpm for all cuttings being steeper than in the vertical hole.

Duan et al. (2008b, a) and Peden et al. (1990) reported that pipe rotation in a vertical well has rotational movement that spins cuttings outward and pushes cuttings away to a location with low annular velocity. This movement may cause cuttings to settle due to the cutting slip velocity being higher than the annular velocity. Pipe rotation also creates vibration movement around the drill pipe, which helps cuttings re-enter regions of high annular velocity; in this case, cuttings are continually transported to the surface, and the mechanism of cutting transport in a vertical hole is somehow not as effective as that in a horizontal well.

In a horizontal well, as shown in Figs. 9–13, a cutting bed consistently forms on the lower side of the wellbore, and rotational movement of the drill pipe will stir the cuttings and consistently move them into an area of higher annular flow. However, all CTR values reach a threshold value above 60 rpm, and the increases from 60 to 150 rpm are insignificant.

3.2. Optimum pipe rotation

Martin et al. (1987) reported that an increase in drill pipe rotation speed from zero will measurably increase the average particle rise velocity. However, there is a threshold value beyond which a further increase in rotation speed appears to have no effect on the particle rise velocity. Figs. 4–13 show the highest CTR increase within 2.14–7.97% when the pipe rotational speed is increased from 0 to 60 rpm, depending on the cutting size, hole angle and polypropylene bead concentration. However, the CTR increase is almost negligible when the pipe rotational speed is increased from 60 to 120 rpm and from 120 to 150 rpm, i.e., within the ranges of 0.02–0.73% and 0.01–0.55%, respectively.

This study shows that pipe rotation is good for hole cleaning, which does not suggest that a higher pipe rotational speed provides a better means of hole cleaning. Moreover, experimental results indicate that a higher rotational speed will tend to make the cuttings break into smaller pieces. Hence, in this study, 60 rpm was considered the optimal rotational speed for the combined parameters within the scope of this study as an approach for drilling optimization.

3.3. Effects of cutting size

Fig. 14 shows CTR vs. cutting sizes for WBM with various polypropylene bead concentrations in a vertical hole at 60 rpm. The smallest cutting size, 0.5–1.0 mm, has the highest CTR at all polypropylene bead concentrations with CTRs ranging from 86.55 to 91.57%, followed by 1.0–1.4 mm with CTRs ranging from 80.79 to 91.14%, 1.4–1.7 mm with CTRs ranging from 77.13 to 90.74% and 1.7–2.0 mm with CTRs ranging from 72.52 to 80.09%. As the cutting size increases from 0.5 – 1.0 mm to 1.7–2.0 mm, the CTR decreases for all polypropylene concentrations. The CTR for the smallest cuttings, 0.5–1.0 mm, yields better transport than that for larger cuttings measuring 1.0–1.4 mm, 1.4–1.7 mm, and 1.7–2.0 mm; at 0 ppb polypropylene beads, the CTRs increase by 5.76%, 9.42%, and 14.03%; at 2 ppb polypropylene beads, the CTRs increase by 3.31%, 6.77% and 8.03%; at 4 ppb polypropylene beads, the CTRs increase by 1.81%, 3.99%, and 5.16%; at 6 ppb polypropylene beads, the CTRs increase by 1.25%, 1.85%, and 3.23%; and at 8 ppb polypropylene beads, the CTRs increase by 0.43%, 0.83%, and 2.48%, respectively.

Fig. 15 shows CTR vs. cutting sizes for WBM with various polypropylene concentrations in a horizontal hole at 60 rpm. The smallest cutting size, 0.5–1.0 mm, has the highest CTR at all polypropylene concentrations, with CTR values ranging from 76.72 to 88.44%, followed by cuttings measuring 1.0–1.4 mm with CTRs in the range 76.02–87.63%, cuttings measuring 1.4–1.7 mm with CTRs in the range 73.57–86.54% and cuttings measuring 1.7–2.0 mm with CTRs in the range 65.81–84.10%.

As the cutting size increases from 0.5 – 1.0 mm to 1.7–2.0 mm, the CTR significantly decreases for all polypropylene concentrations. The CTR for the smallest cuttings, 0.5–1.0 mm, yields better transport than

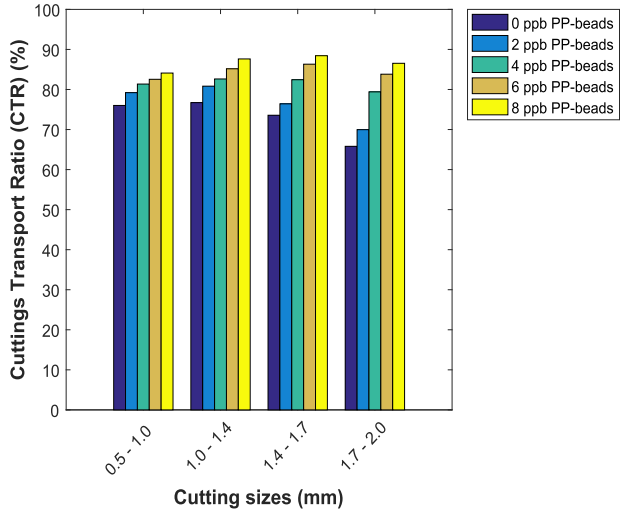


Fig. 15. Cutting sizes in horizontal hole with pipe rotational speed of 60 rpm.

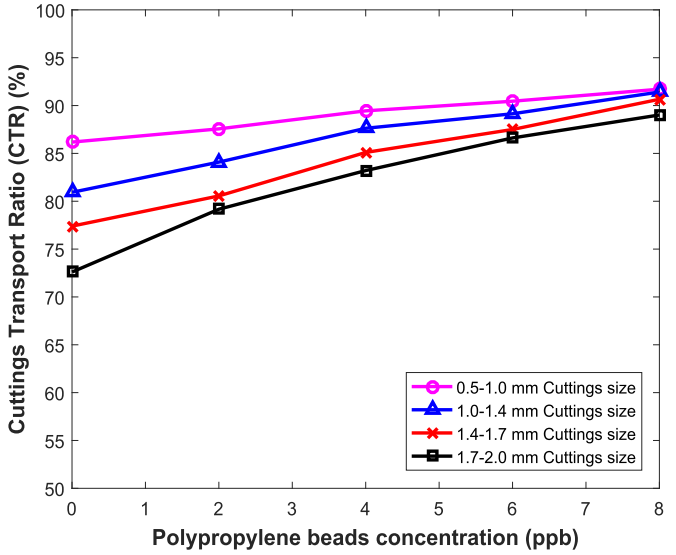


Fig. 16. CTR of different cutting sizes with various polypropylene bead concentrations in vertical hole.

the CTRs of all larger cuttings measuring 1.0–1.4 mm, 1.4–1.7 mm, and 1.7–2.0 mm; at 0 ppb polypropylene beads, the CTRs increase by 0.70%,3.15%, and 10.91%; at 2 ppb polypropylene beads, the CTRs increase by 1.62%, 4.41% and 6.75%; at 4 ppb polypropylene beads, the CTRs increase by 1.27%, 3.22%, and 6.94%; at 6 ppb polypropylene beads, the CTRs increase by 1.15%, 2.50%, and 7.19%; and at 8 ppb polypropylene beads, the CTRs increase by 0.81%, 1.90%, and 4.34%, respectively.

In a vertical hole, the difference between the CTR for cuttings measuring 0.5–1.0 mm and that for cuttings measuring 1.7–2.0 mm at 0 ppb is highly significant, 14.03%. However, when 8 ppb polypropylene beads are introduced into the mud system, the difference in CTR between the smallest and largest cuttings decreases to only 2.48%. The CTR difference is higher when no polypropylene beads are used. Similarly, in the horizontal annulus, the CTR difference between the smallest and largest cuttings is minimal with 8 ppb polypropylene beads in WBM. Polypropylene beads undeniably contribute to better cutting lifting, particularly for larger cuttings.

Cutting transport for smaller cuttings is better than that for larger cuttings at all polypropylene concentrations and hole angles. This result can be explained by the effect of the cutting slip velocity on the cuttings. The cutting slip velocity, also known as the slip velocity, is the velocity at which cuttings naturally fall down due to their density. The movement of cuttings is opposed by the annular velocity of the drilling mud and mud properties that counteract cuttings. To effectively clean a hole, the effect of the upward direction of drilling mud and mud properties must be greater than the settling tendency of cuttings. Otherwise, cuttings will fall down and form a cutting bed. Table 7 shows the slip velocity and drag force for each cutting size.

Table 2 indicates that the cutting slip velocity increases as the cutting size increases. This result explains the trend of larger cuttings having a lower CTR due to their tendency to settle at the bottom of the annulus.

3.4. Effects of polypropylene bead concentration

Fig. 16 shows the CTR vs. various polypropylene concentration for different cutting sizes in a vertical annulus at 60 rpm. Here, 0 ppb polypropylene beads represents WBM without polypropylene beads, which has the lowest CTR among all cutting sizes. The CTR increases as the concentration of polypropylene increases and reaches its highest level when 8 ppb polypropylene is used in WBM. The effect of introducing 2 ppb polypropylene beads into WBM shows a significant CTR improvement of 1.32–6.74%, depending on the cutting size. The CTR increase for WBM containing 4 ppb polypropylene beads is within 2.08–4.06%; that for WBM containing 6 ppb polypropylene beads is within 0.74–3.67%; and that for WBM containing 8 ppb polypropylene beads is within 1.41–3.43%. The smallest cuttings, 0.5–1.0 mm, have the highest CTR at various concentrations of polypropylene. Conversely, the largest cutting size, 1.7–2.0 mm, has the highest CTR increase of 16.57% due to the increase in the concentration of polypropylene beads from 0 to 8 ppb.

Fig. 17 shows the CTR vs. various polypropylene bead concentrations for different cutting sizes in a horizontal annulus at 60 rpm. WBM without polypropylene beads has the lowest CTR for all cutting sizes. CTR increases as the concentration of polypropylene beads increases and reaches the highest level when 8 ppb polypropylene beads is used in WBM. The effect of introducing 2 ppb polypropylene beads into WBM shows a significant CTR improvement of 3.11–4.85%, depending on the

Table 7
Final velocity at various polypropylene bead concentrations and cutting sizes.

Concentration of	Mass of	0.5–1.0 mm	1.0–1.4 mm	1.4–1.7 mm	1.7–2.0 mm
Polypropylene	Polypropylene Bead	Slip velocity, u_t (m/s)			
bead	**(kg)**	0.02574	0.04406	0.05903	0.07225
(ppb)		**Final velocity, Vf (m/s)**			
2	0.8571	2.216	2.206	2.198	2.191
4	1.7143	3.039	3.032	3.026	3.022
6	2.5714	3.466	3.461	3.456	3.453
8	3.4286	3.727	3.723	3.719	3.717

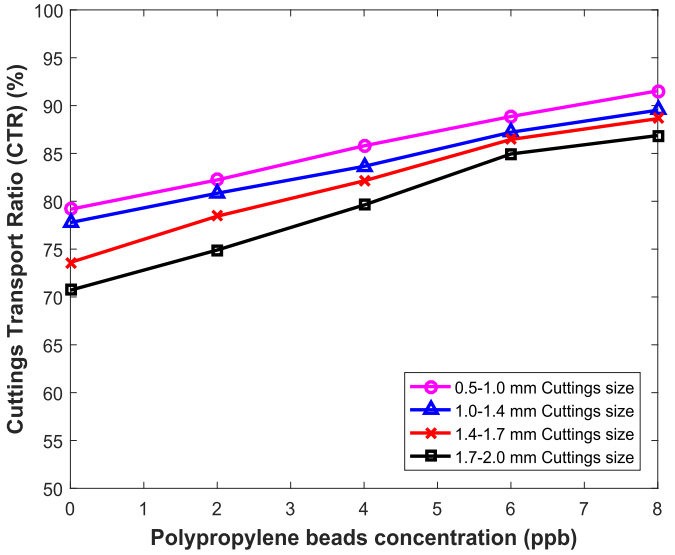


Figure 17. CTR of different cutting sizes with various polypropylene bead concentrations in horizontal hole.

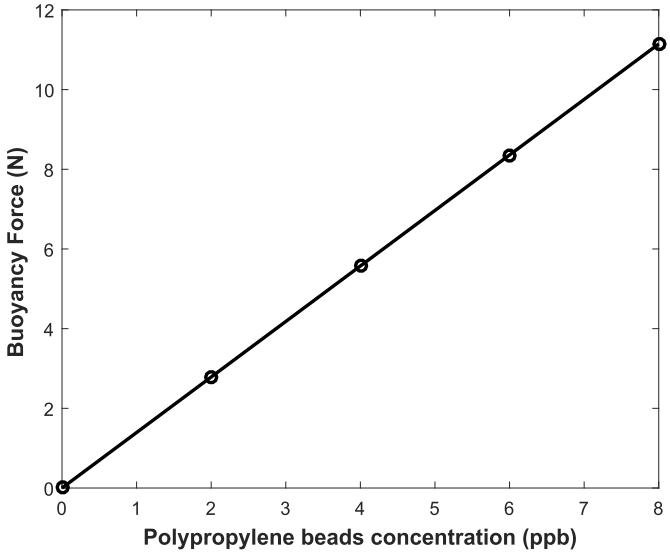


Fig. 18. Buoyancy force at various polypropylene bead concentrations.

cutting size. The CTR increase for WBM with 4 ppb polypropylene beads is within 2.80–4.44%; that for WBM containing 6 ppb polypropylene beads is within 3.18–5.41%; and that for WBM containing 8 ppb polypropylene beads is within 1.72–2.56%. The smallest cuttings, 0.5–1.0 mm, have the highest CTR at various concentrations of polypropylene. However, the largest cutting size, 1.7–2.0 mm, has the highest CTR increment of 15.73% due to the increase in the concentration of polypropylene beads from 0 to 8 ppb.

In summary, increasing the polypropylene bead concentration linearly increases the CTR. Figs. 16 and 17 show that polypropylene beads significantly increase the CTR by up to 16.57% in the vertical hole and by up to 15.73% in the horizontal hole. This result can be explained by the effect of the low density of polypropylene beads. Table 6 shows the effect of increasing the polypropylene concentration, which creates a buoyancy force acting upon the polypropylene by drilling mud.

In this experiment, buoyancy force or upthrust is an upward force exerted by drilling mud that opposes the weight of an immersed object. The density of the cuttings is 2400 kg/m^3, which is greater than the density of the drilling mud, 1198.26 kg/m^3, thereby explaining the behavior of the cuttings. In contrast, the density of polypropylene is 900 kg/m^3, which is less than that of the drilling mud; hence, polypropylene beads produce a buoyancy force. Increasing the volume and concentration of polypropylene beads results in a greater buoyancy force acting on the cuttings.

Fig. 18 shows the linear relation between the polypropylene bead concentration and the buoyancy force exerted by the drilling mud.

By referring to Archimedes principle, if the buoyancy force is greater than an objects weight, then the object will rise to the surface. It was observed that polypropylene beads consistently rose upward in drilling mud throughout the experiment due to their lower density. As the polypropylene beads moved upward in the turbulent and high-velocity drilling mud, polypropylene beads collided with cuttings at their own velocity. Due to the action of internal friction between cuttings and polypropylene, kinetic energy was not conserved, and an inelastic collision occurred. The inelastic collision, however, did obey the conservation of momentum, producing the same final velocity, V_f, for both cuttings and polypropylene beads. As shown in Table 7, V_f increased with increasing polypropylene bead concentration and decreasing cutting size.

The inelastic collision between polypropylene beads and cuttings had a strong effect on cuttings. The final velocity of the cuttings was significantly greater than their respective slip velocity, minimizing the tendency of the cuttings to slip and settle to the bottom of the hole and improving the transport of cuttings. The impulse time, i.e., the time of collision, was 0.82 s. The impulsive force due to the collision of polypropylene beads of varying concentrations and all cuttings was as shown in Table 8 and Fig. 19.

Table 6
Buoyancy force created at various polypropylene bead concentrations.

Concentration	Mass	Volume	Buoyancy
	of Bead	of Bead	Force,
(ppb)	**(g)**	**(10^{-3})m^3**	F_b **(N)**
0	–	–	–
2	857.14	0.952	2.786
4	1714.29	1.905	5.573
6	2571.43	2.857	8.36
8	3428.57	3.81	11.146

4. Conclusions

In this study, the effects of pipe rotations, cutting sizes and polypropylene bead concentrations on CTR have been investigated under a series of 160 experimental runs, and the following conclusions can be drawn.

1. Smaller cuttings are easier to transport at different pipe rotations, hole angles and polypropylene bead concentrations. This result is because larger cuttings have a relatively higher slip velocity, increasing the tendency to form a cuttings bed at the lower side of the bottom hole or lower side of the well.
2. Pipe rotation improves CTR better in a horizontal hole even though

Table 8
Impulsive force due to inelastic collision at various polypropylene bead concentrations.

Concentration of polypropylene beads **(ppb)**	Impulsive force, F_i **(N)**
0	0
2	2.71
4	3.7
6	4.22
8	4.53

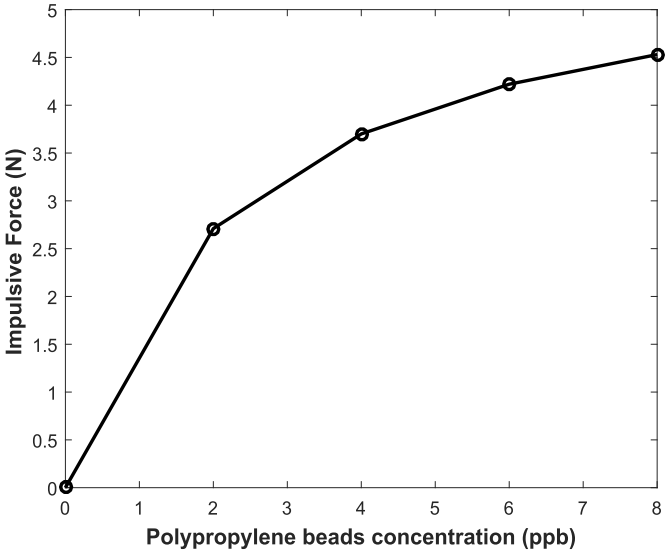


Fig. 19. Impulsive force at various polypropylene bead concentrations.

transporting cuttings in a horizontal hole is more challenging. Pipe rotation also has a higher CTR increase for larger cuttings in vertical and horizontal holes.

3. The optimum pipe rotation for small cutting sizes in less viscous drilling mud of 16 cp is 60 rpm for different polypropylene bead concentrations in vertical and horizontal holes.
4. The CTR increases up to 16.57% in vertical holes and 15.73% in horizontal holes. Polypropylene beads have undoubtedly produced good performance in enhancing mud carrying capacity.
5. Generally, smaller cuttings have a higher CTR than larger cuttings for all polypropylene bead concentrations and pipe rotations in vertical and horizontal holes. However, larger cuttings have a higher CTR difference between 0 ppb and 8 ppb polypropylene beads than smaller cuttings in horizontal holes. This result indicates that polypropylene beads enhance cutting lifting better for large cuttings than small cuttings in horizontal holes. Most importantly, polypropylene beads have significantly increased the CTR.

Conflicts of interest

The authors declare no conflicting interests.

Acknowledgements

The authors wish to express their sincere thanks to the Research Management Centre of University of Technologi Malaysia and the Malaysian Ministry of Higher Learning for providing the needed funds (Vote 4F575).

Nomenclature

ρ	Density
PP	Polypropylene
ID	Inner Diameter
OD	Outer Diameter
F_b	Buoyancy Force
F_i	Impulsive Force
WBM	Water Based Mud
WOB	Weight of Bit
RPM	Revolutions Per Minute
ROP	Rate of Penetration
CTR	Cuttings Transport Ratio
μ_a	Apparent Viscosity
μ_p	Plastic Viscosity
MTV	Minimum Transport Velocity
MCT	Mud Cake Thickness
g	Acceleration due to gravity
m	Mass of particle
u_t	Slip Velocity
V_p	Particle Velocity
V_f	Particle Final Velocity
V_i	Particle Initial Velocity
PAC	Polyanionic Cellulose
COF	Coefficient of Friction
CFD	Computational Fluid Dynamics
CFD–DEM	Computational Fluid Dynamics–Discrete–Element Method

Unit Conversion

1 psi	$\equiv 6894.76$ Pa
°F	$\equiv (^{\circ}C \times 1.8) + 32$
1 m	$\equiv 3.28084$ ft
$\rho\,[g/cm^3]$	$\equiv \frac{141.5}{(131.5 + \gamma\,^{\circ}API)}$
1 m	$\equiv 39.37$ in
1 Pa	$\cdot$ s $\equiv 1000$ cP

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.petrol.2019.04.086.

References

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. Pages 1–9. Society of petroleum Engineers. In: SPE Annual Technical Conference and Exhibition, 1-4 October, Dallas, Texas, https://doi.org/10.2118/63050-MS.

Akhshik, S., Behzad, M., Rajabi, M., 2015. CFD–DEM approach to investigate the effect of drill pipe rotation on cuttings transport behavior. J. Pet. Sci. Eng. 127, 229–244. https://doi.org/10.1016/j.petrol.2015.01.017.

Akhshik, S., Behzad, M., Rajabi, M., 2016. CFD–DEM simulation of the hole cleaning process in a deviated well drilling: the effects of particle shape. Particuology 25, 72–82. https://doi.org/10.1016/j.partic.2015.02.008.

Amanna, B., Reza, M., Movaghar, K., 2016. Cuttings transport behavior in directional drilling using computational fluid dynamics (CFD). J. Nat. Gas Sci. Eng. 34, 670–679. https://doi.org/10.1016/j.jngse.2016.07.029.

API, 2009. Recommended practice for field testing water-based drilling fluids. http://ballots.api.org/ecs/sc13/API_RP13B-1_5Ed_TestingWBDF_4316.pdf, Accessed date: 6 August 2018.

ASTM, 2006. Standard test methods for maximum index density and unit weight of soils using a vibratory table. https://www.astm.org/DATABASE.CART/HISTORICAL/D4253-00.htm, Accessed date: 6 August 2018.

Azar, J.J., Sanchez, R.A., 1997. Important issues in cuttings transport for drilling directional wells. Pages 1–4. Society of petroleum Engineers. In: Latin American and Caribbean Petroleum Engineering Conference, 30 August-3 September, Rio de Janeiro, Brazil, https://doi.org/10.2118/39020-MS.

Beck, R.W., Nuss, W.F., Dunn, T.H., 1947. The Flow Properties of Drilling Muds. Society of Petroleum Engineers, American Petroleum Institute. https://www.onepetro.org/conference-paper/API-47-009.

Becker, T.E., Azar, J.J., 1985. Mud-Weight and Hole-Geometry Effects on Cuttings Transport while Drilling Directionally. Society of Petroleum Engineers, SPE Drilling and Completion. https://www.onepetro.org/general/SPE-14711-MS.

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 . Society of petroleum Engineers. In: Eastern Regional Meeting, 17-19 October, Lexington, Kentucky USA, https://doi.org/10.2118/111208-MS.

Bird, J., Garrett, C., 1996. Co-polymer beads reduce friction in horizontal wells. Society of petroleum Engineers. J. Can. Pet. Technol. https://doi.org/10.2118/96-09-GE.

Bland, R.G., Mullen, G.A., Gonzalez, Y.N., Harvey, F.E., Pless, M.L., 2006. Modeling of effect of drill pipe rotation speed on wellbore cleanout. In: Society of Petroleum Engineers, IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, 13-15 November, Bangkok, Thailand, https://doi.org/10.2118/103731-MS.

Boyou, N.V., Ismail, I., Sulaiman, W.R.W., Haddad, S.A., Hussein, N., Hui, T.H., Nadaraja, K., 2019. Experimental investigation of hole cleaning in directional drilling by using nano-enhanced water-based drilling fluids. J. Pet. Sci. Eng 176, 220–231.

Cho, H., Shah, S.N., Osisanya, S.O., 2002. A three-segment hydraulic model for cuttings transport in coiled tubing horizontal and deviated drilling. Pages 1–8. Petroleum society of Canada. J. Can. Pet. Technol. https://doi.org/10.2118/02-06-03.

Clark, R., Bickham, K., 1994. A Mechanistic Model for Cuttings Transport. Society of Petroleum Engineers, SPE Drilling and Completionhttps://doi.org/10.2118/28306-MS.

Duan, M., Miska, S.Z., Yu, M., Takach, N.E., Ahmed, R.M., Hallman, J.H., 2008a. Experimental study and modeling of cuttings transport using foam with drillpipe rotation. Society of petroleum Engineers. In: SPE Annual Technical Conference and Exhibition, 21-24 September, Denver, Colorado, USA, https://doi.org/10.2118/116300-MS.

Duan, M., Miska, S.Z., Yu, M., Takach, N.E., Ahmed, R.M., Zettner, C.M., 2008b. Transport of Small Cuttings in Extended-Reach Drilling. Society of Petroleum Engineers, SPE Drilling and Completionhttps://doi.org/10.2118/104192-PA.

Egenti, N.B., 2014. Understanding Drill-Cuttings Transportation in Deviated and Horizontal Wells. Society of Petroleum Engineers, SPE Drilling and Completion. https://doi.org/10.2118/172835-MS.

Epelle, E., Gerogiorgis, D.I., 2018a. A CFD investigation of the effect of particle sphericity on wellbore cleaning efficiency during oil and gas drilling. Comput. Aided Chem. Eng. 43, 127–132. https://doi.org/10.1016/B978-0-444-64235-6.50024-3.

Epelle, E., Gerogiorgis, D.I., 2018b. Transient and steady state analysis of drill cuttings transport phenomena under turbulent conditions. Chem. Eng. Res. Des. 131, 520–544. https://doi.org/10.1016/j.cherd.2017.11.023.

Epelle, E., Gerogiorgis, D.I., 2018c. CFD modelling and simulation of drill cuttings transport efficiency in annular bends: effect of particle sphericity. J. Pet. Sci. Eng. 170, 992–1004. https://doi.org/10.1016/j.petrol.2018.06.041.

Epelle, E., Gerogiorgis, D.I., 2017. A multiparametric CFD analysis of multiphase annular flows for oil and gas drilling applications. Comput. Chem. Eng. 43, 127–132. https://doi.org/10.1016/j.compchemeng.2017.08.011.

Ezeakacha, C.P., Salehi, S., 2019. Experimental and statistical investigation of drilling fluid loss in porous media: Part 2 (Fractures). J. Pet. Sci. Eng. 65, 257–266. https://doi.org/10.1016/j.jngse.2019.03.007.

Ford, J.T., Peden, J.M., Oyeneyin, M.B., Gao, E., Zarrough, R., 1990. Experimental investigation of drilled cuttings transport in inclined boreholes. Pages 1–10. In: Society of Petroleum Engineers, SPE Annual Technical Conference and Exhibition, 23-26 September, New Orleans, Louisiana, https://doi.org/10.2118/20421-MS.

Hakim, H., Katende, A., Sagala, F., Ismail, I., Nsamba, H., 2018. Performance of polyethylene and polypropylene beads towards drill cuttings transportation in horizontal wellbore. J. Pet. Sci. Eng. 165, 962–969. https://doi.org/10.1016/j.petrol.2018.01.075.

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). J. Pet. Sci. Eng. 156, 801–813. https://doi.org/10.1016/j.petrol.2017.06.059.

Hussaini, S.M., Drill, J. J. Azar, 1974. Cutting transport in full scale vertical annuli . Society of petroleum Engineers. J. Pet. Technol. https://doi.org/10.2118/10674-PA.

Iyoho, A.W., Azar, J.J., 1981. An accurate slot-flow model for non-newtonian fluid flow through eccentric annuli. Soc. Petrol. Eng. J. 1–8. https://doi.org/10.2118/9447-PA.

Kamyab, M., Rasouli, V., 2016. Experimental and numerical simulation of cuttings transportation in coiled tubing drilling. J. Nat. Gas Sci. Eng. 29, 284–302. https://doi.org/10.1016/j.jngse.2015.11.022.

Larsen, T.I., Pilehvari, A.A., Azar, J.J., 1997. Development of a New Cuttings-Transport Model for High-Angle Wellbores Including Horizontal Wells. Pages 1–7. Society of Petroleum Engineers, SPE Drilling & Completion. https://doi.org/10.2118/25872-PA.

Luo, Y., Bern, P., Chambers, B., 1994. Simple Charts to Determine Hole Cleaning Requirements in Deviated Wells. Society of Petroleum Engineers, SPE Drilling and Completionhttps://doi.org/10.2118/27486-MS.

Majid, N.F.F., Katende, A., Ismail, I., Sagalad, F., MdSharif, N., Yunus, M.A.C., 2018. A Comprehensive Investigation on the Performance of Durian Rind as a Lost Circulation Material in Water Based Drilling Mud. Petroleum. https://doi.org/10.1016/j.petlm.2018.10.004.

Martin, M., Georges, C., Bisson, P., Konirsch, O., 1987. Transport of cuttings in directional wells. Society of petroleum Engineers. In: SPE/IADC Drilling Conference, 15-18 March, New Orleans, Louisiana, https://doi.org/10.2118/16083-MS.

Mohammadsalehi, M., Malekzadeh, N., 2011. Application of new hole cleaning optimization method within all ranges of hole inclinations. In: International Petroleum Technology Conference, International Petroleum Technology Conference, 15-17 November, Bangkok, Thailand, https://doi.org/10.2523/IPTC-14154-MS.

Mohammadzadeh, K., Hashemabadi, S.H., Akbari, S., 2016. CFD simulation of viscosity modifier effect on cutting transport by oil based drilling fluid in wellbore. J. Nat. Gas Sci. Eng. 29, 355–364. https://doi.org/10.1016/j.jngse.2015.11.011.

Moraveji, M.K., Sabah, M., Shahryari, A., Ghaffarkhah, A., 2017. Investigation of drill pipe rotation effect on cutting transport with aerated mud using CFD approach. Adv. Powder Technol. 28 (4), 1141–1153. https://doi.org/10.1016/j.apt.2017.01.020.

Nazari, T., Hareland, G., Azar, J.J., 2010. Review of cuttings transport in directional well drilling: systematic approach. Pages 1–15. In: Society of Petroleum Engineers, SPE Western Regional Meeting, 27-29 May, Anaheim, California, USA, https://doi.org/10.2118/132372-MS.

Ogunrinde, J.O., Dosunmu, A., 2012. Hydraulics optimization for efficient hole cleaning in deviated and horizontal wells. Pages 1–16. In: Society of Petroleum Engineers, Nigeria Annual International Conference and Exhibition, 6-8 August, Lagos, Nigeria, https://doi.org/10.2118/162970-MS.

Ozbayoglu, M., Sorgun, M., Saasen, A., Svanes, K., 2010a. Modeling of effect of drill pipe rotation speed on wellbore cleanout . Society of petroleum Engineers. J. Can. Pet. Technol. https://doi.org/10.2118/136689-PA.

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. In: Society of Petroleum Engineers, IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, 25-27 August, Jakarta, Indonesia, https://doi.org/10.2118/114965-MS.

Ozbayoglu, M.E., Saasen, A., Sorgun, M., Kamya, K.S., 2010b. Critical fluid velocities for removing cuttings bed inside horizontal and deviated wells. Petrol. Sci. Technol. 6, 594–602. https://doi.org/10.1080/10916460903070181.

Pang, B., Wang, S., Wang, Q., Yang, K., Lu, H., Hassan, M., Jiang, X., 2018. Numerical prediction of cuttings transport behavior in well drilling using kinetic theory of granular flow. J. Pet. Sci. Eng. 161, 190–203. https://doi.org/10.1016/j.petrol.2017.11.028.

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. J. Pet. Sci. Eng. 174, 201–215. https://doi.org/10.1016/j.petrol.2018.11.009.

Peden, J., Ford, J., Oyeneyin, M., 1990. Comprehensive experimental investigation of drilled cuttings transport in inclined wells including the effects of rotation and eccentricity. In: Society of Petroleum Engineers, European Petroleum Conference, 21-24 October, the Hague, Netherlands, https://doi.org/10.2118/20925-MS.

Pigott, R.J.S., 1941. Mud Flow in Drilling. American Petroleum Institute. https://www.onepetro.org/conference-paper/API-41-091.

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. J. Petrol. Explor. Prod. Technol. 2 (3), 149–156. https://doi.org/10.1007/s13202-012-0031-0.

Rooki, R., M. A, A.F.D., M, N., 2018. CFD simulation of rheological model effect on cuttings transport. J. Dispersion Sci. Technol. 36 (3), 402–410. https://doi.org/10.1080/01932691.2014.896219.

Sanchez, R.A., Azar, J.J., Bassal, A., Martins, A., 1999. Effect of drillpipe rotation on hole cleaning during directional-well drilling. Society of Petroleum Engineers, SPE Journal. https://doi.org/10.2118/56406-PA.

Saxena, A., Pathak, A.K., Ojha, K., Sharma, S., 2017. Experimental and modeling hydraulic studies of foam drilling fluid flowing through vertical smooth pipes. Egyptian J. Petrol. 26 (4), 279–290. https://doi.org/10.1016/j.ejpe.2016.04.006.

Sayindla, S., Lund, B., Ytrehus, J.D., Saasen, A., 2017. Hole-cleaning performance comparison of oil-based and water-based drilling fluids. J. Pet. Sci. Eng. 159, 49–57. https://doi.org/10.1016/j.petrol.2017.08.069.

Scomi, 2018. Drilling Fluids. http://www.scomigroup.com.my/GUI/pdf/drilling_fluid.pdf, Accessed date: 6 August 2018.

Sifferman, T.R., Myers, G.M., Haden, E.L., Wahl, H.A., 1974. Drill cutting transport in full scale vertical annuli . Society of petroleum Engineers. J. Pet. Technol. https://doi.org/10.2118/4514-PA.

Skalle, P., 2010. Drilling Fluid Engineering. Ventus Publishing Company ISBN 978-87-403-1139-6. https://bookboon.com/en/drilling-fluid-engineering-ebook.

Sun, X., Wang, K., Yan, T., Shao, S., Jiao, J., 2014. Effect of drillpipe rotation on cuttings transport using computational fluid dynamics (CFD) in complex structure wells. J. Petrol. Explor. Prod. Technol. 4 (3), 255261. https://doi.org/10.1007/s13202-014-0118-x.

Terry, H., Ravi, K., 2010. Modeling of Effect of Drill Pipe Rotation Speed on Wellbore Cleanout . Society of Petroleum Engineers, IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, 1-3 November. Ho Chi Minh City, Vietnam. https://doi.org/10.2118/135703-MS.

Thomas, R.P., Azar, J.J., Becker, T.E., 1982. Drillpipe eccentricity effect on drilled cuttings behavior in vertical wellbores. Society of petroleum Engineers. J. Pet. Technol. https://doi.org/10.2118/9701-PA.

Tomren, P.H., Iyoho, A.W., Azar, J.J., 1986. Experimental Study of Cuttings Transport in Directional Wells. Pages 1–14. Society of Petroleum Engineers, SPE Drilling Engineering. https://doi.org/10.2118/12123-PA.

Walker, S., Li, J., 2000. The Effects of Particle Size, Fluid Rheology, and Pipe Eccentricity on Cuttings Transport. Society of Petroleum Engineers, SPE/ICoTA Coiled Tubing Roundtable, 5-6 April. https://doi.org/10.2118/60755-MS. Houston, Texas.

Werner, B., Myrseth, V., Saasen, A., 2017. Viscoelastic properties of drilling fluids and their influence on cuttings transport. J. Pet. Sci. Eng. 156, 845–851. https://doi.org/10.1016/j.petrol.2017.06.063.

Williams, C., Bruce, G., 1951. Carrying capacity of drilling muds. Society of petroleum Engineers. J. Pet. Technol. https://doi.org/10.2118/951111-G.

Yan, X., Ariaratnam, S.T., Dong, S., Zeng, C., 2018. Horizontal directional drilling: state-of-the-art review of theory and applications. Tunn. Undergr. Space Technol. 72, 162–173. https://doi.org/10.1016/j.tust.2017.10.005.

Yeu, W.J., Katende, A., Sagala, F., Ismail, I., 2019. Improving hole cleaning using low density polyethylene beads at different mud circulation rates in different hole angles. J. Nat. Gas Sci. Eng. 61, 333–343. https://doi.org/10.1016/j.jngse.2018.11.012.

Yi, T.T., Ismail, I., Katende, A., Sagala, F., Mugisa, J., 2017. Experimental investigation of cuttings lifting efficiency using low and high density polyethylene beads in different hole angles. J. Mater. Sci. Appl. 3 (5), 71–78. http://article.aascit.org/file/pdf/8910898.pdf.

Ytrehus, J.D., Carazza, L., Lund, B., Kosberg, B.R., Gyland, K.R., Taghipour, A., Saasen, A., 2018. Cuttings bed removal in deviated wells. In: American Society of Mechanical Engineers, ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering, pp. 1–7. https://doi.org/10.1115/OMAE2018-77832.

Yu, M., Melcher, D., Takach, N., Miska, S.Z., Ahmed, R., 2004. A New Approach to Improve Cuttings Transport in Horizontal and Inclined Wells. Society of Petroleum Engineers, SPE Drilling and Completionhttps://doi.org/10.2118/90529-MS.

Zeng, C., Yan, X., Zeng, Z., Yang, S., 2018. The formation and broken of cuttings bed during reaming process in horizontal directional drilling. Tunn. Undergr. Space Technol. 76, 21–29. https://doi.org/10.1016/j.tust.2018.03.008.



Nursyafiqah S. Heshamudin was born in Malaysia. She holds Petroleum Engineering degrees from the the University of Tekhnologi Malaysia(UTM). She is currently working with the Society of Petroleum Engineers as an Event Administrative Assistant supporting the workshop portfolio in the Asia Pacific Region from Upstream to Downstream sector in the oil and gas industry. She is a certified member of Society of Petroleum Engineers.



Allan Katende is born and raised in Uganda, educated in a British and Norwegian school system. At the time of publication, he holds an Msc. Petroleum Engineering with great honour from the Norwegian University of Science and Technology in 2015 and a Bsc. Mechanical Engineering where he graduated as a valedictorian from Makerere University, College of Engineering, Design, Art and Technology in 2013. He has several industry experience on Oil and Gas Exploration, Production and Recovery from the Norwegian Continental Shelf, Shale Oil & Gas production in Texas, USA and in Uganda. He is actively involved in both teaching and research and his research and teaching interests include; Drilling Engineering with emphasis on Drilling Fluids, Hole Cleaning, Well Control; Well Construction and Well Integrity; Fluid Flow and Transport in Porous Media; Experimental and Numerical Simulation of Enhanced Oil Recovery methods; Thermodynamics; Nanotechnology and its applications in Engineering; Materials Science; Fractured Reservoirs; Reservoir Engineering in general; Shale Well Modeling and Decline Curve Analysis; Data driven modeling; Petrophyiscs; Physiochemical and Environmental Engineering; Fluid Mechanics; Multiphase Flow; Production Engineering; Engineering Mechanics & Mechanics of Materials. He has also worked at the Department of Geoscience and Petroleum at the Norwegian University of Science and Technology as a Graduate Teaching Asssistant for Fractured Reservoirs.



Halimatun A. Rashid holds a BSc in Petroleum Engineering from Universiti Teknologi Malaysia. She is a Graduate Research Assistant and currently completing her master (by research) program which focuses cuttings transport behaviour in water-based mud. She is a certified member of Society of Petroleum Engineers.



Issham Ismail is an Associate Professor at Department of Petroleum Engineering, Universiti Teknologi Malaysia. He is also a Chartered Engineer of the UK Council and Institute of Marine, Science and Technology. His research interests are in well completion, formation evaluation, drilling fluid, hole cleaning, petroleum production, applications of nanotechnology in petroleum engineering, and flow assurance. He is actively involved in both teaching and research, and has published many novelty articles in international journals. His great achievement is the publication of single authored three well completion and slickline operations books by UTM Press.



Farad Sagala is currently pursuing a PhD in Petroleum Engineering at the University of Calgary focussing on applications of nanoparticles for enhancing oil recovery. He holds an Msc in Petroleum Engineering (Summa Cumlaude) from the University of Technology Malaysia in 2015 and a Bsc. in Bio-systems and Mechanical Engineering from Makerere University in 2013. He has knowledge on using various Experimental and simulations techniques with use of various softwares across the petroleum engineering value chain. His Research interests involve the applications of nanoparticles for enhancing oil recovery in the oil and gas industry.



Ariffin Samsuri is a Professor at Department of Petroleum Engineering, Universiti Teknologi Malaysia and a certified member of Society of Petroleum Engineers. He is actively involved in teaching and research, and has published many articles in international journals. His research interests are wellbore stability, sand control, cement & cementing technology, drilling mud material & drilling optimization, petroleum production optimization, research & development management, biofuel, and nanotechnology application in oil and gas.