



The effect of drill–pipe rotation on improving hole cleaning using polypropylene beads in water-based mud at different hole angles

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Abstract

Hole cleaning is always a problem, particularly during drilling operations, and drilling fluid plays an important role in transporting drill cuttings through an annular section of wellbore to the surface. To transport the cuttings, a water-based mud with added polypropylene beads was selected since it is environmentally friendly and cost efficient. The polypropylene beads help to transport cuttings by providing an additional buoyancy force that lifts the cuttings to the surface via the influence of collision and drag forces. This experiment was performed using a 20 ft test section, 10 ppg drilling mud and 0.86 m/s annular velocity in a laboratory scale rig simulator, and the concentration of polypropylene beads was varied from 0 to 8 ppb. As the concentration of polypropylene increases, the cutting transport ratio also increases. It was observed that the fewest cuttings are lifted at a critical angle of 60°, followed by 45°, 30°, 90° and 0°. Additionally, cutting sizes had moderate effects on the cutting lifting efficiency, where smaller cutting sizes (0.5–1.0 mm) are easier to lift than larger cutting sizes (2.0–2.8 mm). Furthermore, a study of buoyancy force and impulsive force was conducted to investigate the cutting lifting efficiencies of various concentrations of polypropylene beads. This lifting capacity was also assisted by the presence of polyanionic cellulose (PAC), which increases the mud carrying capacity and is effective for smaller cuttings. The results show that in the presence of pipe rotation, the cutting lifting efficiency is slightly enhanced due to the orbital motion provided by the drill pipe for better hole cleaning. In conclusion, polypropylene beads combined with pipe rotation increase the cutting transport ratio in the wellbore.

Keywords Hole cleaning · Cutting transport ratio · Hole angles · Pipe rotation · Water-based mud · Cutting size

Abbreviation

OBM	Oil-based mud
SBM	Synthetic-based mud
WBM	Water-based mud
CTR	Cuttings transport ratio
RPM	Revolutions per minute
MTV	Minimum transport velocity
F_B	Buoyancy force
g	Acceleration due to gravity
m	Mass of particle

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

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Introduction

Drilling fluids have routinely been used in the oil and gas industry for several years, and such fluids have served many roles, such as balancing formation pressures in the wellbore, lubricating the drill string and so forth (Beck et al. 1947; Bland et al. 2006; Duan et al. 2008; Hussaini and Azar 1974; Katende et al. 2019; Ozbayoglu et al. 2010; Pigott 1941; Saboori et al. 2018; Salehi et al. 2016; Saxena et al. 2017; Sayindla et al. 2017; Shu and Ma 2016;

Sifferman et al. 1974; Werner et al. 2017). Nevertheless, an essential role of drilling fluid is to lift cuttings from the drill bit through the annular section and to the surface (Becker and Azar 1985; Clark and Bickham 1994; Frigaard et al. 2017; Heshamudin et al. 2019; Luo et al. 1994; Majid et al. 2018; Onuoha et al. 2015; Shu and Zhang 2018a, b; Yu et al. 2004). It is difficult to proceed with the drilling process without removing the cuttings. For vertical wells, cutting lifting can typically proceed without any difficulties, but for a deviated well, there are difficulties in transporting the cuttings because they may accumulate, forming either a stationary bed at hole angles greater than 50° or a moving bed at lower angles (Williams and Bruce 1951). Hence, the seriousness of cutting lifting varies depending on the amount and the location of cuttings distributed along the wellbore (Clark and Bickham 1994; Egenti 2014; Hareland et al. 1993; Kamyab and Rasouli 2016; Nazari et al. 2010; Pang et al. 2019; Zeng et al. 2018b).

With directional drilling and extended-reach wells becoming popular, factors such as increased torque and drag force have become increasingly more significant (Amanna et al. 2016; Dushaishi et al. 2016; Frank and Ting 2014; Gavignet and Sobey 1989; Hovda 2019; Mamat et al. 2013; Piroozian et al. 2012; Yan et al. 2018a, b; Zeng et al. 2018a). This is particularly true for water-based muds (WBM), which generate a high coefficient of friction (COF) between the drill string and the wellbore, resulting in higher torque and drag force.

In addition, WBMs are able to amplify the wear rates in the wellbore. Oil-based muds (OBMs) and synthetic-based muds (SBMs) typically generate a lower COF compared to WBMs, particularly when they involve contact between the formation and steel. Nevertheless, the use of OBMs and SBMs is restricted due to their high costs and environmental effects. Furthermore, drilling fluids can impact wellbore integrity due to cement contamination during drilling (Li and Radonjic 2019). It will therefore be better to develop environmental friendly WBMs that are as lubricious as OBMs and SBMs (Growcock et al. 1999). With the technical application and economic benefits of drilling wells at high angles, especially from a vertical level, there has been a problem in controlling the behavior of drill cuttings in the well, which has proven to be costly.

Moreover, we lack the ability to control annular environments Becker and Azar (1985). In addition to transporting cuttings, the distribution of cuttings in the wellbore is affected not only by pipe rotation but also cutting sizes and fluid properties, especially in eccentric situations (Ozbayoglu et al. 2004, 2008; Peden et al. 1990; Sanchez et al. 1999; Walker and Li 2000). In general, the presence of pipe rotation will gradually reduce stationary cutting beds in the wellbore. The circular motion of the drill string may

be the basis for the effect of inclination on pressure drop, even though no cuttings are visible.

Normally, the mixing of polymer beads, such as polypropylene beads, with WBM has proven (Hakim et al. 2018; Yeu et al. 2019; Yi et al. 2017) to be successful in reducing the slip velocity of cuttings, which makes the polymer bead buoyant in the mud, thus causing a reduction in the Reynolds number of particles. The decrease in the Reynolds number of particles results in an increase in drag force (Bird and Garrett 1996; Skalle 2010; Williams and Bruce 1951). The increase in drag force results in better mud lifting capacity for a good wellbore cleaning at various angles, such as vertical, horizontal and even deviated conditions (Onuoha et al. 2015; Ozbayoglu et al. 2004).

Hakim et al. (2018) investigated the performances of polyethylene and polypropylene beads in transporting drill cuttings in a horizontal wellbore. Their analysis involved using a mud formulation reported by Scomi (2018), to observe the effect of polymer beads on hole cleaning. The results showed that polymer beads improved the hole cleaning efficiency.

From these studies (Akhshik et al. 2015; Bilgesu et al. 2007; Boyou et al. 2019; Hemphill and Ravi 2010; Moraveji et al. 2017; Oseh et al. 2019; Ozbayoglu et al. 2008; Pang et al. 2018; Peden et al. 1990; Rooki et al. 2018; Sanchez et al. 1999; Sun et al. 2014), the following question arises: to what extent does the effect of pipe rotation improve hole cleaning using polypropylene beads in WBM at different hole angles? This question forms the basis of this study to clarify the effect of pipe rotation on hole cleaning at different hole angles. This is because polypropylene beads provide a buoyancy force, which would provide an additional lifting capacity in the form of collision and drag in the drilling fluid due to their less dense nature that aids in lifting cuttings in a highly efficient manner from the wellbore to the surface.

Experimental setup and methods

The purpose of this study is to investigate the effect of pipe rotation on cutting lifting efficiency using different concentrations of polypropylene beads in WBM at different hole angles. This study was conducted in two stages. The first stage involved the use of basic WBM, and the second stage was performed using five different concentrations (0, 2, 4, 6 and 8 ppb) of polypropylene beads. Each stage was conducted using five different hole angles (0°, 30°, 45°, 60° and 90°) and in the presence of pipe rotation (0 and 120 RPM) to determine the effect of hole angle on cutting lifting efficiency.

Laboratory scale flow loop rig simulator

A laboratory scale flow loop rig simulator (Fig. 1) was used to investigate the effect of pipe rotation using polypropylene beads in WBM at different hole angles.

Material preparation

Sand samples

The sand samples were collected, washed and heated in an oven for 24 h at 60°C. After heating, the sand samples were sieved using a sieve shaker to obtain the desired particle sizes. Different sizes of sieve trays (4.00, 2.80, 2.00, 1.70, 1.40, 1.00 and 0.50 mm) were used to obtain different cutting size ranges (0.50–0.99 mm, 1.00–1.39 mm, 1.40–1.69 mm, 1.7–1.99 mm, 2.00–2.79 mm and 2.80–4.00 mm). The sieved sands were then weighed using an electronic balance and placed in sealable plastic bags.

Polypropylene beads

Figure 2 shows the polypropylene beads used in this study. Polypropylene beads are used to provide buoyancy force to improve cutting lifting efficiency. Moreover, the beads are spherical, opaque and have a density of 0.90 g/cc, and their size ranges from 2–3 mm. The beads are inert; thus, they do not chemically react with the drilling fluid. The beads can also be recycled for upcoming operations. Four concentrations of polymer beads (2, 4, 6 and 8 ppb) were added to the WBM.



Fig. 2 Polypropylene beads

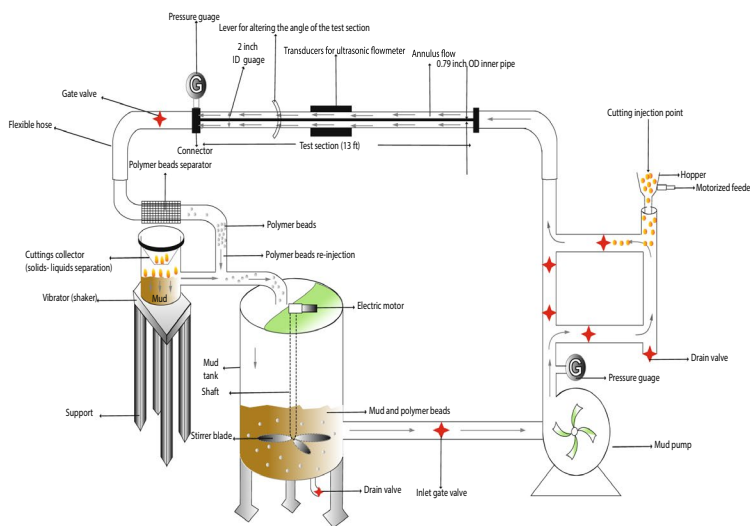
Drilling mud

The experiment was performed with five different concentrations of polypropylene beads with Miswaco (2018) mud formulation. To simulate the actual drilling fluid being used in the oil and gas industry for deep water drilling operations, a density of 10 pounds per gallon (ppg) was set to prepare the basic WBM in Table 1.

To obtain the desired mud density, barite was added to each lab barrel for each concentration of polypropylene beads, as listed in Table 2.

Experimental procedure

The experiment was conducted using a laboratory scale rig simulator at ambient temperature. The experimental procedure was adapted to determine the effects of pipe rotation



(a) Schematic of the flow loop Rig Simulator



(b) Lay out of the Flow Loop Rig Simulator.

Fig. 1 Flow loop rig simulator

Table 1 Water-based mud formulation

Additives	Composition
Fresh water	150 L
Bentonite	4285.71 g
Caustic soda	107.14 g
PAC-HV	214.29 g
Xanthan gum	321.43 g
Barite	39840.00 g

Table 2 Weight of barite needed for different polypropylene concentrations

Type of Mud	Weight of Barite Added(g)
WBM	39840.00
WBM + 2 ppb Polypropylene beads	39334.29
WBM + 4 ppb Polypropylene beads	40088.57
WBM + 6 ppb Polypropylene beads	40092.86
WBM + 8 ppb Polypropylene beads	40594.29

on hole cleaning using polypropylene beads at different hole angles in WBM. Before starting the experiment, all the parts of the rig simulator (Fig. 1) were examined to avoid any leakage of drilling fluid and to ensure that each part is completely sealed to avoid contamination. As mentioned previously, the study was conducted in two stages, which required two types of drilling mud systems to be used, where basic WBM and five different concentrations of polypropylene beads (0, 2, 4, 6 and 8 ppb) were used.

To test the cutting lifting ability of basic mud, the test section was set at 0° (vertical angle) and without any pipe rotation; the basic mud was circulated in the flow loop system until it achieved stabilization. Then, cuttings were injected into the system and flowed for approximately 5 min. Subsequently, the valve connecting to the separation unit was opened and allowed to flow for 7 min to determine the cutting lifting efficiency of basic mud at 0° without any pipe rotation.

After 7 min, the valve was immediately closed, and the lifted cuttings were collected, washed, dried, weighed and recorded. The dried cuttings were reused and injected into the flow loop. The experiment was repeated using different hole angles (30°, 45°, 60° and 90°) by following the same procedure mentioned previously without any pipe rotation. Once the data for all hole angles were collected, the same procedure was repeated with pipe rotation.

After completing the first stage, the same procedure was used for the second stage, where the basic mud was mixed with different concentrations of polypropylene beads. At the end of each run, the mud system was flushed to the separation unit to retrieve the cuttings and polypropylene beads

manually before proceeding with different concentrations of beads. At the separation unit, the sieve acts as a medium to trap both cuttings and polypropylene beads, where both of them were placed in a pail of water. Due to their lower density, the beads tend to float, and the cuttings settle at the bottom of the pail. Then, the cuttings were obtained, washed, dried and weighed.

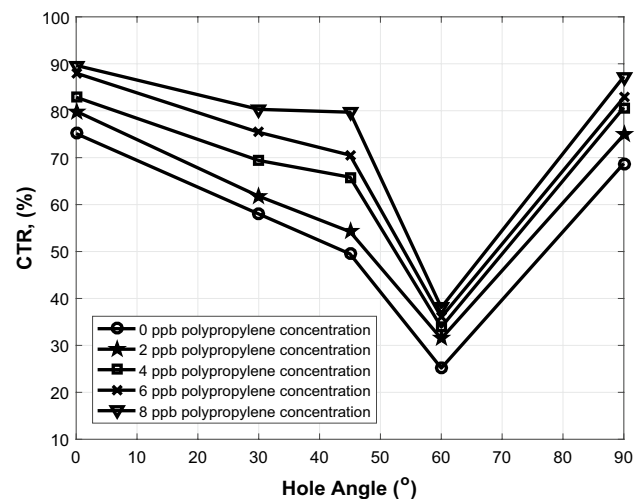
The collected data were recorded, and the cutting transport ratio (CTR) was calculated using Eq. 1. Hence, the CTRs of all hole angles were compared and analyzed for their efficiency in lifting cuttings.

$$CTR, (\%) = \frac{\text{Recovered injected drilled cuttings}}{\text{Initial injected drilled cuttings}} \times 100 \quad (1)$$

Results and discussion

Performance of polypropylene beads at different angles without pipe rotation

A plot of CTR versus hole angle was analyzed, as shown in Fig. 3 (cutting size of 0.5–1.0 mm) and Fig. 4 (cutting size of 2.0–2.8 mm). For smaller cuttings, the CTR was found to be the lowest at 60°, followed by 45°, 90°, 30° and 0°. According to Peden et al. (1990) and Clark and Bickham (1994), the minimum transport velocity (MTV) is the highest at hole angles from 40° to 60°, and it experiences a drastic reduction at hole angles above 60°. This behavior occurs because at lower angles (below 60°), the

**Fig. 3** Cutting transport ratio vs. hole angle for cuttings size of 0.5–1.0 mm and pipe rotation of 0 RPM

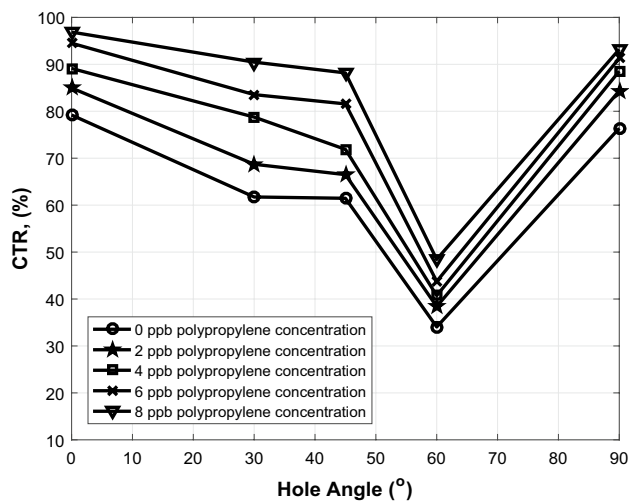


Fig. 4 Cutting transport ratio vs. hole angle for cuttings size of 2.0–2.8 mm and pipe rotation of 0 RPM

cuttings experience a lifting mechanism, which requires a higher MTV to lift the cuttings, and the mechanism shifts into a rolling mechanism at higher angles (above 60°), which requires a lower MTV for better cutting lifting. The CTR at the critical angle of 60° ranges from 54.5 % to 63.4 %. In addition, the CTR for the least critical angle of 0° ranges from 84.1 % to 89.2%. At the horizontal angle, the CTR ranges from 74.1 % to 81.7%, which is lower than that of the vertical angle. Hole angle has minor effects on stationary bed formation at angles from 70° to 90° (Duan et al. 2008).

As shown in Fig. 4 (cutting size of 2.0–2.8 mm), the CTR was the lowest at 60° , followed by 45° , 30° , 90° and 0° . For larger cutting sizes, the CTR was significant at the vertical angle because larger cuttings experience less drag and torque compared to smaller cuttings (0.5–1.0 mm). Smaller cuttings experience a lower MTV for cutting rolling/sliding, and stationary bed formation decreases, which results in a higher cutting transportation compared to larger cuttings (Duan et al. 2008).

Peden et al. (1990) determined that larger cuttings are more difficult to transport, especially at angles above 60° . The CTR at the critical angle of 60° ranges from 25.2 % to 38.1 %. Moreover, the CTR for the least critical angle of 0° ranges from 75.1 % to 89.7 %. At the horizontal angle, the CTR ranges from 68.8 % to 87.3 %, which is less than that of the vertical angle due to the formation of sand dunes.

In addition, the increase in the concentration of polypropylene beads causes a significant increase in the CTR for both cutting sizes (Figs. 3 and 4). At 0.5–1.0 mm, the CTR for the vertical angle increases from 85.2 % at 0 ppb to 87.4% at 6 ppb. Meanwhile, at 2.0–2.8 mm, the CTR at the vertical angle increases from 75.1 % to 88.0 %. This result

indicates that polypropylene beads do provide an increase in cutting lifting efficiency regardless of the hole angle.

Performance of Polypropylene Beads at Different Angles with Pipe Rotation

In Figs. 5 (0.5–1.0 mm) and 6 (2.0–2.8 mm), the CTR versus hole angle graph is plotted and analyzed for a pipe rotation of 120 RPM. The hole angle pattern remains similar to Figs. 3 and 4, where 60° is the most critical angle, and the least critical angle for both cutting sizes is 0° . However, there is a significant increase in the CTR value due to the presence of pipe rotation. For example, at the critical angle,

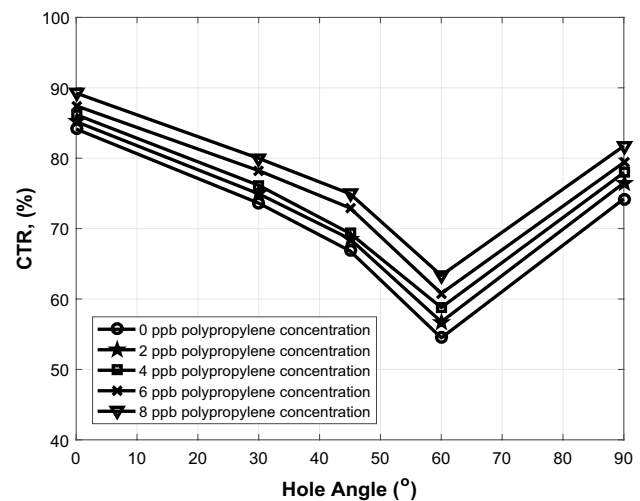


Fig. 5 Cutting transport ratio vs. hole angle for cuttings size of 0.5–1.0 mm and pipe rotation of 120 RPM

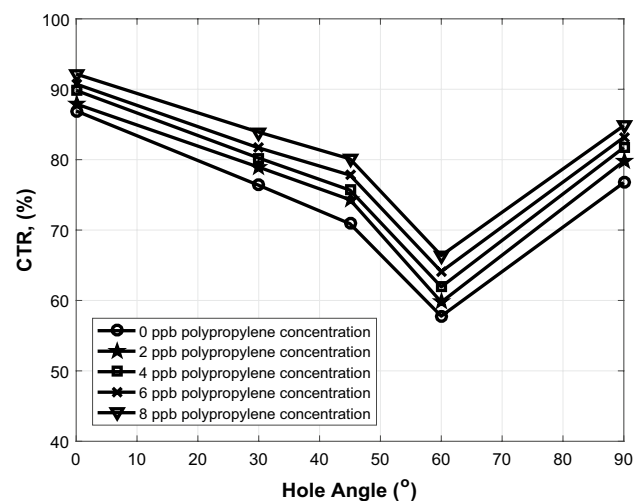


Fig. 6 Cutting transport ratio vs. hole angle for cuttings size of 2.0–2.8 mm and pipe rotation of 120 RPM

the CTR value for smaller cuttings increases from 54.5 % to 57.8 % and increases from 25.2 % to 34.1 % for larger cuttings at 0 ppb. The CTR for the least critical angle of 0° increases from 84.1 % to 86.9 % for smaller cuttings at 0 ppb and increases from 75.1 % to 79.2 % for larger cuttings at 0 ppb. This result is due to the orbital motion of the drill pipe that reduces the concentration of cuttings in the lower annular section that causes a mechanical agitation, which lifts the cuttings to the surface (Sanchez et al. 1999).

As shown in Figs. 5 and 6, the presence of polypropylene beads aids in increasing the cutting lifting efficiency for both cutting sizes. At 0.5–1.0 mm, the CTR for the vertical angle increases from 86.9 % at 0 ppb to 90.7 % at 6 ppb for 120 RPM. Meanwhile, at 2.0–2.8 mm, the CTR at the vertical angle increases from 79.2 % at 0 ppb to 96.1 % at 6 ppb for 120 RPM. Thus, this result confirms that the presence of pipe rotation aided by the increased concentration of polypropylene helps to improve the transport of cuttings at all hole angles.

Comparison between smaller and larger cutting sizes at the critical angle of 60°

Figures 7 and 8 show that the smallest cutting size (0.5–1.0 mm) lifted the most cuttings from 0 ppb to 8 ppb (54.5–63.4 %) compared to the largest cutting size (2.0–2.8 mm), which lifted the fewest cuttings (25.2 %–38.1 %), at the critical angle of 60° without the presence of pipe rotation. This result might be due to the viscous drilling mud, which contains polyanionic cellulose (PAC), a viscosifying agent. In the presence of PAC solutions that increase the mud carrying capacity, smaller cuttings are greatly

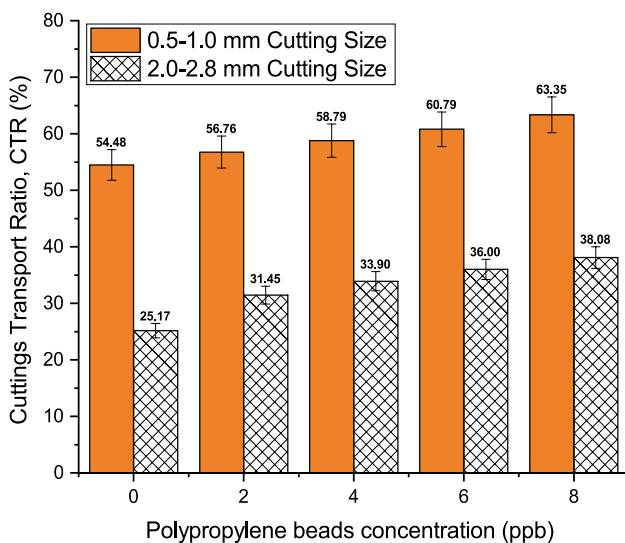


Fig. 7 CTR versus polypropylene bead concentration for both cutting sizes without pipe rotation (0 RPM)

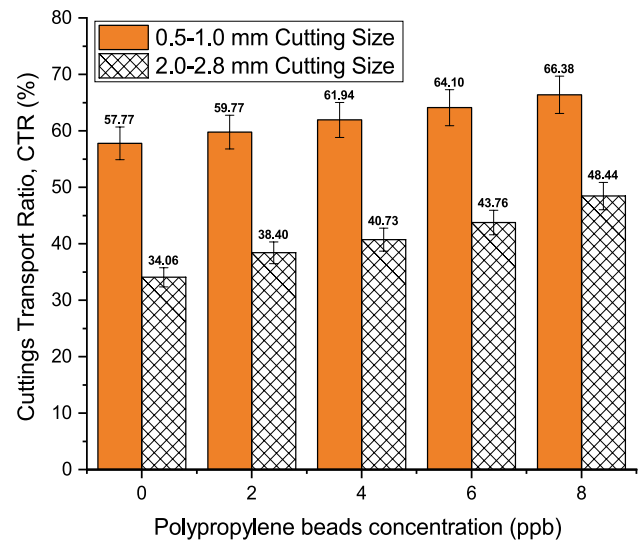


Fig. 8 CTR versus polypropylene bead concentration for both cutting sizes with pipe rotation (120 RPM)

lifted, whereas the lifting of larger cuttings is slightly enhanced (Duan et al. 2008). In addition, pipe rotation slightly increases the CTR for both cutting sizes. For small cuttings (0.5–1.0 mm), the CTR increases from 54.5 % to 57.8 %, and the CTR for larger cuttings (2.0–2.8 mm) increases from 25.2 % to 34.1 % for 0 ppb. This result indicates that pipe rotation does have a significant effect on the lifting of cuttings.

Buoyancy force influence on lifting the cuttings

According to buoyancy theory, a less dense particle floats in a dense medium, thus creating a buoyancy force. The density of polypropylene beads is 0.9 g/cc, and the beads flow in a much denser drilling fluid that has a density of 1.198 g/cc. Using the buoyancy force equation, the phenomenon of polypropylene beads creating buoyancy force can be investigated.

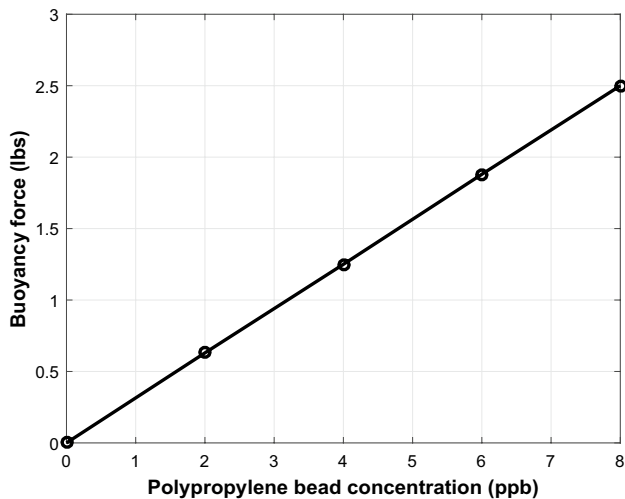
$$F_B = g \cdot V_p (\rho_f - \rho_b) \quad (2)$$

Equation 2 is used to determine the buoyancy force. Then, the sum volume of polypropylene beads is used in the equation to calculate the total additional buoyancy force acting on the cuttings. The results are shown in Table 3.

As shown in Table 3 and Fig. 9, the buoyancy force increases as the polypropylene bead concentration increases. This result thus verifies the increase in CTR when the polypropylene bead concentration increases, as shown in Figure 8.

Table 3 Buoyancy force of polypropylene beads acting on cuttings

Polypropylene concentration (ppb)	Mass of beads Injected (g)	Volume of beads Injected (cc)	Buoyancy force, (lbs)
0	0	0	0
2	857.14	953.38	0.63
4	1714.29	1904.77	1.25
6	2571.43	2857.14	1.88
8	3428.57	3809.52	2.5

**Fig. 9** Buoyancy force of polypropylene beads acting on cuttings

Effect of impulsive force created from collision of polypropylene beads and cuttings

In addition to buoyancy force, impulsive force is another reason for effective cutting lifting. This is due to the impact between cuttings and polypropylene beads that causes cuttings to be lifted. According to this experiment, the mud density is 10 ppg (equivalent to 1.198 g/cc), and the annular velocity used in this experiment is 0.86 m/s. The impulsive force equation is given in Eq. 3

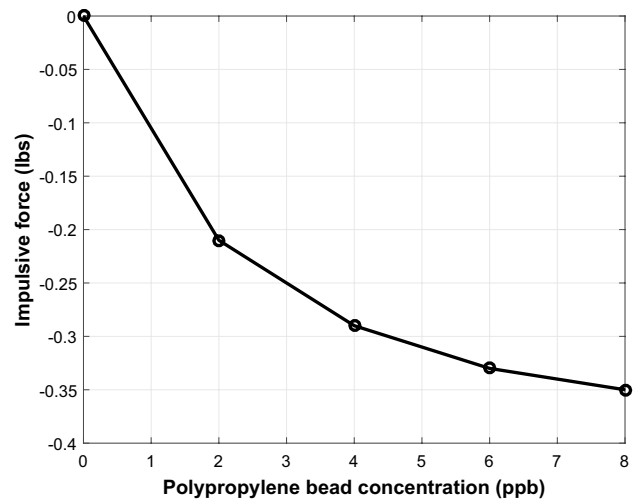
$$\text{Impulsive force} = m \cdot (V_f - V_i) \quad (3)$$

The calculated impulsive forces due to the collision between polypropylene beads and cuttings are tabulated in Table 4.

As shown in Fig. 10, the increase in polypropylene bead concentration causes an increase in impulsive force. This result also proves that a higher polypropylene concentration causes an increase in CTR, where 8 ppb is the largest and 2 ppb is the lowest. In conclusion, 8 ppb polypropylene beads result in the highest impulsive force and buoyancy forces, thus confirming that the increase

Table 4 Impulsive forces of polypropylene beads

Polypropylene concentration (ppb)	Impulsive Force
0	0
4	-0.29
6	-0.33
8	-0.35

**Fig. 10** Impulsive force versus polypropylene beads concentration

in polypropylene concentration directly relates to the increase in cutting lifting efficiency.

Conclusions

1. The performance of polypropylene beads is more significant at the vertical angle of 0° because cuttings are uniformly distributed throughout the annular section and settle faster, whereas the worst angle is at 60° because the MTV is the highest at hole angles from 40° to 60°.
2. As the concentration of polypropylene beads increases, the CTR also increases for all hole angles, which is imperative for hole cleaning.
3. Polypropylene beads provide an increase in CTR for both smaller and larger cuttings. However, smaller cuttings provide a better yield due to the presence of PAC solution, which increases the mud carrying capacity compared to larger cuttings.
4. Pipe rotation slightly increases the CTR because the orbital motion of pipe rotation causes an increase in frictional pressure loss, thus significantly reducing stationary bed formation.

5. With the help of pipe rotation and increased concentration of polypropylene beads, there is a drastic increase in the CTR that is efficient for hole cleaning.
6. The contribution of impulsive force and buoyancy forces is directly related to the increase in CTR.

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