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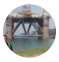

Issham Ismail
Universiti Teknologi Malaysia

Allan Katende
Oklahoma State University - Stillwater

Sagala Farad
The University of Calgary

Mugisa John
Universität Bremen

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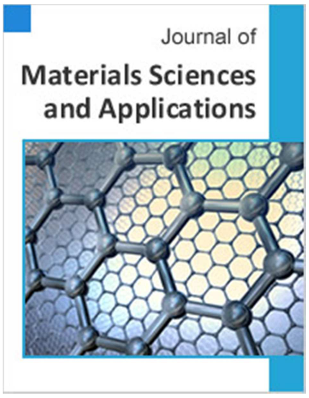

Experimental Investigation of Cuttings Lifting Efficiency Using Low and High Density Polyethylene Beads in Different Hole Angles

Tan Tin Yi[1], Issham Ismail[1], Allan Katende[2, *], Farad Sagala[3], John Mugisa[4]

[1]Department of Petroleum Engineering and Renewable Energy, Univesrsiti Teknologi Malaysia (UTM), Johor, Malaysia
[2]Department of Geoscience and Petroleum, Norwegian University of Science and Technology, Trondheim, Norway
[3]Department of Chemical and Petroleum Engineering, University of Calgary, Alberta, Canada
[4]Department of Petroleum Engineering, International University of East Africa, Kampala, Uganda

Email address
allan_katende@hotmail.com (A. Katende)
[*]Corresponding author

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Abstract
This study investigates the impact of low and high density polyethylene beads on wellbore cleaning using water-based mud at different hole angles of 0°, 60°, and 90°. The polyethylene beads concertation is varied from 1 to 5% by volume. Experimental investigations were accomplished using 11ft long acrylic concentric annulus flow test section with a 1.80in casing inner diameter equipped with a fixed inner pipe of 0.85in as the outer diameter. A total of 66 runs were completed using sand of size ranging from 1.18 – 2.00mm and density of 2.65 g/cc. Mud density and viscosity were maintained at 10 ppg and 7cp respectively, in a flow velocity of 0.80m/s. The densities of low and high density polyethylene beads were 0.92 g/cc and 0.96 g/cc respectively while their size was 3mm in spherical shape. The introduction of polyethylene beads were found to be more efficient in the vertical hole in which the incremental cuttings transport ratio was more than 15% being registered. This was due to sufficient buoyancy force provided by the low density polyethylene beads to counteract the gravity force and reduce the slip velocity of cuttings due to their low densities. In addition, the impulsive force due to collision between beads and sand enabled the cuttings to be lifted more efficiently.

1. Introduction

Transportation of cuttings and efficiency of the hole cleaning has been cited as one of the major concerns during drilling and development of oil and gas wells. However, with a well-designed drilling program, operational cost and rig time can significantly be reduced. By controlling the cuttings transport variables such as flow rate, fluid velocity, fluid viscosity, flow regime, mud weight, hole angle, drill-pipe diameter, drill-pipe rotational speed, drill-pipe eccentricity and rate of penetration, the hole cleaning problem can be minimized; [1, 2].

Directional and horizontal drilling techniques have recently gained popularity. However, these techniques still face the possibility of getting high torque and drag, [3-6].

Mirhaj et al (2012) [5] and Ismail et al (2013) [6] reported that the use of water-based mud (WBM) increases the coefficients of friction (COF) between the drill pipe and the wellbore, hence creating torque and drag. On the other hand, Polipropilena et al (2015) [7], asserts that the use of oil-based mud (OBM) and synthetic-based mud (SBM) generally produces a lower COF compared to WBM. However, due to environmental concerns, the use of OBM was recently prohibited in many areas, leaving WBM as the only best alternative. Mamat et al (2013) [8]. Considering the hole angles between 40° to 60°, the cuttings lifting efficiency is the worst as it is hard to achieve an effective hole cleaning Turbulent flow is more effective than laminar flow in lifting drilled cuttings in highly deviated holes ie; 55° to 90°. However, the laminar flow serves better in low angle wells between 0° to 45°, Egenti et al (2014) [10]

The Idea of introducing the polymer beads in water-based mud was to reduce the slipping velocity of drilled cuttings due to polyethylene's specific gravity which is smaller than that of water. This is sought to provide the expected buoyancy force in mud consequently reducing the Reynolds Number of the mud which eventually increases the coefficient of drag. According to Skalle (2011) [11], an increase in coefficient of drag translates into a high drag force experienced during transportation off drilling fluid and thus increases the cuttings transport efficiency in vertical, horizontal and inclined holes.

Ramadan et al (2001) [16], looked into a mechanistic model for cuttings removal from solid bed inclined channels. Their results indicate that the erosion rate tests of three beds with different bed particle size ranges show that beds with intermediate bed particle size have the maximum erosion rate.

Beads are not new, they are already used for drilling and well intervention operations. Skalle et al (1999) [17], evaluated microbeads as lubricant in drilling muds using a modified lubricity tester. Their results show that particles like barite and cuttings alter the friction of a drilling mud. Their evaluation also investigated smaller polymer microbeads which will pass unhindered. The results indicated that microbeads reduce the friction in water based muds with around 40% which is significantly better than other commercial lubricants.

2. Materials and Methods

2.1. Polyethylene Beads

The experimental investigation used two types of polymer beads in water-based mud namely < low density polyethylene (LDPE) beads and high density polyethylene (HDPE) beads. These are very tough and resilient to any chemicals. Most importantly, the densities of LDPE and HDPE are 7.7 ppg and 8ppg respectively which are less than the basic water-based mud (WBM) used in this laboratory work (10ppg) and typical sandstone of 12ppg. Therefore, LDPE and HDPE could travel upwards with a higher velocity due to buoyancy and collide with cuttings from the wellbore to surface. Buoyancy and impulsive forces are the significant factors in determining the performance of LDPE and HDPE beads.

Based on the buoyancy theory, a buoyancy force is created when the less dense particle is submerged in a denser medium. The equation of buoyancy is used to justify he LDPE and HDPE which are able to create buoyancy force and subsequently may result in positive hole cleaning. Equation (1) as used by; Wai et al [12], shows that the buoyancy force is directly proportional to the particles volume.

$$F_B = gV_p(\rho_F - \rho_B) \quad (1)$$

Where FB is the buoyancy force, g is the gravity acceleration coefficient m/s^2, V_p is the cuttings particle volume, cm^3, ρ_F and ρ_B is the density of cuttings and beads in g/cm^3 respectively.

In addition to buoyancy force, the collision between LDPE and HDPE beads with drilled cuttings creates an impulse force and the change in momentum when an object hits on another object with a certain amount of force over a short period of time. Consequently, the impulsive force either speeds up or slows down the collided objects. Impulsive force, F_{imp} is given as;

$$F_{imp} = (m\Delta V)t \quad (2)$$

Where; m is the mass, g; V is the volume and t is the time.

2.2. Mud Rheological Properties Determination

Plain water-based mud (WBM) and WBM containing five different concentrations of LDPE and HDPE beads were prepared in order to determine their rheological properties. The preparation of basic WBM was based on the Scomis formulation (ie, to get the desired mud density of 10 ppg, 350 ml of tap water was mixed with 40 g of bentonite, 453 g of barite and 0.25 g of soda-ash). The weight of barite addition is shown in Table 1. The results of rheological properties are shown in Tables 2, 3, and 4.

Table 1. *Weight of additional barite in different concentrations.*

Types of mud	Weight of additional barite (g)
WBM	145
WBM + 1% LDPE	151
WBM + 2% LDPE	158
WBM + 3% LDPE	163
WBM + 4% LDPE	171
WBM + 5% LDPE	176
WBM + 1% HDPE	146
WBM + 2% HDPE	151
WBM + 3% HDPE	158
WBM + 4% HDPE	163
WBM + 5% HDPE	168

Table 2. *Basic water-based mud with LDPE and HDPE mud rheological properties before aging.*

Types of Mud	Rheological Properties						
	ρ	μ	μ	YP	GS	FL	MCT
	(ppg)	(cp)	(cp)	(lb/ft^2)	10s-10m	(ml)	(/32in)
WBM	10	9	7	5	3 - 8	10.0	2.31
WBM+1%LDPE	10	9	7	5	3- 8	11.2	2.53
WBM+2%LDPE	10	9	7	5	3- 8	14.2	2.70
WBM+3%LDPE	10	9	7	5	3 - 8	15.2	2.95
WBM+4%LDPE	10	9	7	5	3 - 8	15.4	3.30
WBM+5%LDPE	10	9	7	5	3 - 8	16.0	3.62
WBM+1%HDPE	10	9	7	5	3 - 8	21.0	2.60
WBM+2%HDPE	10	9	7	5	3 - 8	21.2	2.88
WBM+3%HDPE	10	9	7	5	3 - 8	22.4	3.22
WBM+4%HDPE	10	9	7	5	3 - 8	23.2	3.48
WBM+5%HDPE	10	9	7	5	3 - 8	23.8	3.64

Table 3. *Basic water based mud and water based mud with LDPE and HDPE mud rheological properties after aging.*

Types of Mud	Rheological Properties						
	ρ	μ	μ	YP	GS	FL	MCT
	(ppg)	(cp)	(cp)	(lb/ft^2)	10s-10m	(ml)	(/32in)
WBM	10	21	15	26	3-25	14.2	2.30
WBM+1%LDPE	10	21	15	26	4-25	14.4	2.90
WBM+2%LDPE	10	21	15	26	5-25	15.0	3.38
WBM+3%LDPE	10	21	15	26	6-25	16.2	3.72
WBM+4%LDPE	10	21	15	26	7-25	16.8	4.29
WBM+5%LDPE	10	21	15	26	8-25	17.8	4.60
WBM+1%HDPE	10	21	15	26	9-25	15.4	2.56
WBM+2%HDPE	10	21	15	26	10-25	16.2	2.90
WBM+3%HDPE	10	21	15	26	11-25	16.8	3.38
WBM+4%HDPE	10	21	15	26	12-25	17.8	3.72
WBM+5%HDPE	10	21	15	26	13-25	18.6	4.00

Table 4. *Basic water-based mud with LDPE and HDPE in a HPHT Test.*

Type of mud	HPHT	
	Filtrate Loss Volume (cc)	Mud Cake Thickness (/32in)
WBM	35.00	10.90
WBM+1%LDPE	32.50	11.26
WBM+2%LDPE	30.40	12.70
WBM+3%LDPE	28.90	13.70
WBM+4%LDPE	26.40	15.37
WBM+5%LDPE	25.00	16.30
WBM+1%HDPE	34.00	10.25
WBM+2%HDPE	32.50	11.26
WBM+3%HDPE	30.40	12.67
WBM+4%HDPE	28.90	13.68
WBM+5%HDPE	27.40	14.69

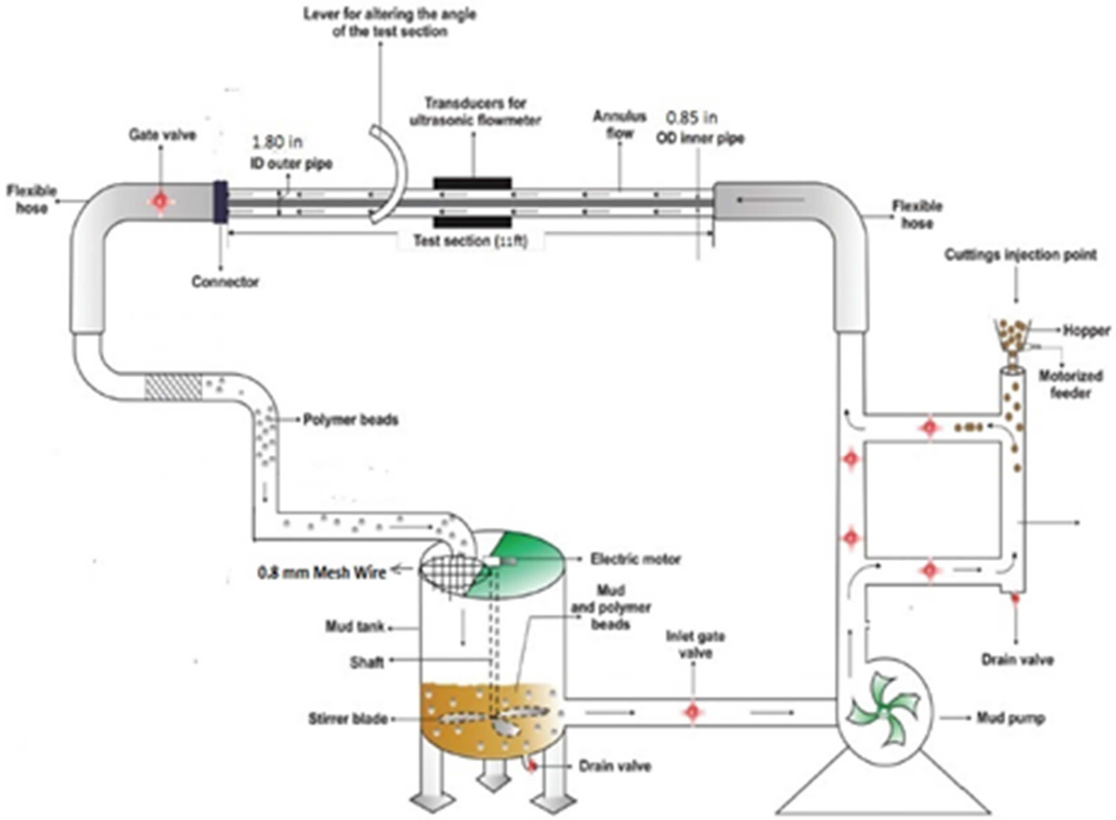
2.3. Hole Cleaning Operation

The flow loop shown in Figure 1 was fabricated to allow the observation of mud flow behaviour. This acrylic pipe serving as borehole was 11 ft long with 1.80 in as the inner diameter (ID). Inside this pipe was 11 ft long hollow Polyvinyl Chloride (PVC) pipe, 0.85 in OD with both ends sealed to avoid flow through the inner pipe. Sand (collected from Desaru beach in Johor Malaysia) preparation involved drying in an oven followed by sorting in sizes of 1.18 – 2.00 mm using a sieve shaker. The sieved sands were weighed at 200 g each using an electronic balance and sealed in a plastic bag. A variable speed pump with a 3-phase induction motor of 2811 rpm and 2 hp (1.5 kW) was used to circulate the drilling mud throughout the transport column.

The capacity was sufficient to achieve steady experimental flow rates and an ultrasonic flow meter was attached to the pipe in order to measure the instantaneous mud flow rate. A mud tank with capacity of 190 litres having a stirrer driven by 0.25 hp (0.18kW) electric motor of 1350 rpm was installed on the mud tank to ensure proper mixing of the mud and homogeneous incorporation of polymer beads in the drilling mud. After stabilizing the annular velocity at 0.8 m/s, the flow was by-passed to the separation tank unit by opening the valve to the separation tank and closing the by-pass valve to the mud tank. The drilling mud was after that re-channelled to allow fluid flow through the cuttings and then up to the top of the test section before all transported cuttings were collected at the separation unit. Circulation time of 6 minutes was recorded for each run using a stop watch right after the flow was re-channelled through cuttings.

The collected cuttings were then washed, dried and weighed to evaluate the percentage of recovery of the drilled cuttings. The process was repeated for all different concentrations and types of PE beads at different hole inclinations. Equation 3 was used to calculate the cuttings transport ratio for LDPE and HDPE beads;

$$CTR = \frac{FinalDriedWeight}{InitialDriedWeight} x100 \quad (3)$$



(a) Experimental flow loop

(b) Layout of the flow loop

Figure 1. *Experimental Set-Up.*

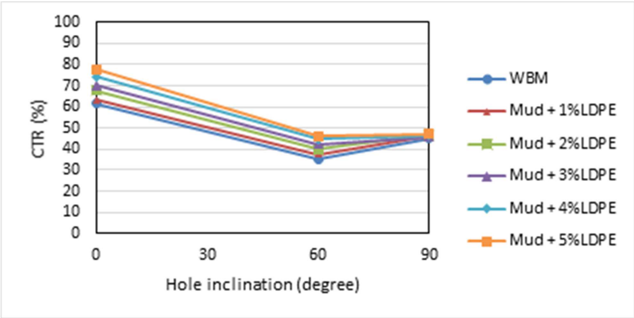


Figure 2. *Concentration of LDPE in different hole angles.*

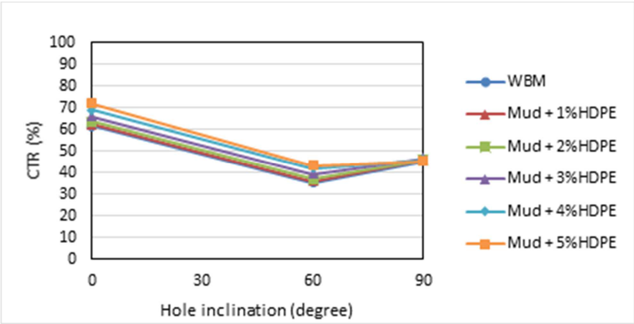


Figure 3. *Concentration of HDPE in different hole angles.*

3. Results and Discussions

3.1. Effect of Hole Inclination

Figure 2 shows the cuttings transport ratio against hole inclination using different concentrations (1-5% by volume) of LDPE beads. In a vertical hole (0°), the cuttings lifting efficiency of each concentration of beads is better than other hole angles. If the hole angle increases, there is a negative influence on cuttings transports. At higher degrees of inclination, the tendency of downward cuttings bed sliding is more likely to occur which increases the hydraulic requirement for adequate hole cleaning [2, 13]. For instance, cuttings transport ratio of 5% LDPE in a vertical hole is 77.56%, more than the horizontal angle (90°) and 60° angle which is 47.20% and 46.20% respectively. While in the angle of 60°, it was found to have the worst cuttings transport ratio for every concentration of beads.

In addition, for a vertical and a 60° hole; increase in concentration of low density beads translated into an increase in cuttings transport ratio. For example, at 1% LDPE, the cuttings transport ratio was 63.30% and it increased to 7.56% for 5% LDPE. However, in a horizontal hole, the low density beads did not provide any significant result in lifting cuttings ratio due to the cuttings tendency to settle at the bottom of the test section and the beads floating above during mud flow. Figures 2&3 show the same cuttings transport ratio against hole inclination using different concentrations (1-5% by volume) of HDPE beads. In the angle of 60° (Figure 5), the incremental CTR was lower than for the vertical hole. This was perhaps due to the buoyancy effect of the polymer beads where they tend to flow at the upper section of the hole while drilled cuttings tend to settle at the lower part of the hole thereby making polymer beads unable to extend an up-thrust effect to the particles effectively [14]. On the other hand, the horizontal hole had the worst CTR increment as the beads did not have any function in hole cleaning. This can be explained in terms of the floatation of the beads at the top of the horizontal section while cuttings are moving at the bottom, hence no collision (no impulsive force and buoyancy force to provide a sustainable force to lift the cuttings).

3.2. Effects of Beads Density and Concentration

Figure 4 illustrates the cuttings transport ratio versus polyethylene beads concentration in a vertical hole. It is clearly shown that the LDPE beads have higher cuttings transport ratio than high density beads for each concentration. For instance, 5% LDPE has 77.56% CTR and it reduced to 72.20% CTR for 5% HDPE. This is because the LDPE has a lower density than HDPE which is 0.92 g/cc and 0.96 g/cc respectively, hence LDPE has higher buoyancy force to push the cuttings upward and thus a better hole cleaning. Both of the densities show a general increase in trend from 1 to 5% of beads concentration. For example, the 1% LDPE increased from 63.30% to 77.56% CTR and 5% HDPE increased from 62.5% to 72.2% CTR.

When the concentration of beads increases, the buoyancy force increases as well. This is because the buoyancy force is directly proportional to the volume of beads [15]. There is a minor effect on cuttings lifting efficiency in 1% concentration as the low and high density polyethylene beads have a 63.30% and 62.5% CTR respectively. Figure 5 shows the cuttings transport ratio against polyethylene beads (low and high density) at various concentrations. The CTR is observed to increase gradually in both polymer beads at concentration ranges of 1% to 5% ie the CTR's are 37.50%, 39.90%, 42.60%, 44.90%and 46.20% respectively. While for HDPE, the CTR's are 36.10%, 37.10%, 39.40%, 41.90% and 43.40% respectively. From this result, it is apparent that low density beads have a higher CTR than high density beads in every concentration meaning that low density beads have a better hole cleaning.

On the other hand, Figure 6 demonstrates cuttings transport ratio against polyethylene beads in a horizontal angle. In this angle, there is no significant improvement observed in cuttings lifting efficiency for both densities. This is because the density of beads is lower than the mud which provides the buoyancy force, thus the beads tend to float at the top of the horizontal section, and cuttings settle and move at the bottom section, [15] which means the beads do not have collision with cuttings. Figure 7, shows incremental cuttings transport ratio against both PE beads in different hole angles. It is evident that the increase in CTR for LDPE beads is higher than HDPE beads for every angle. Theoretically, this is true because LDPE beads have a lower density than HDPE, thus creation of a greater buoyancy force.

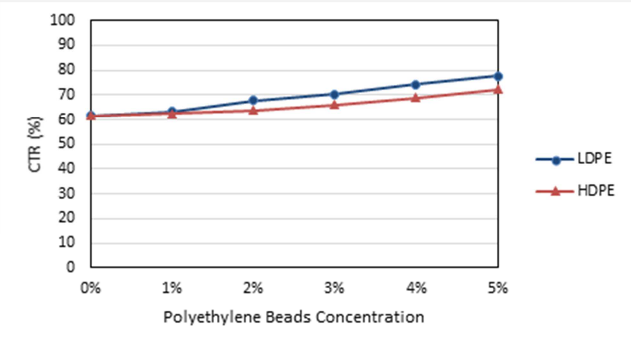


Figure 4. CTR for LDPE and HDPE beads in a vertical hole.

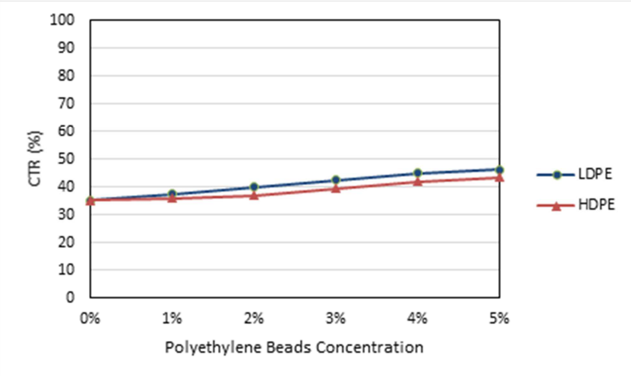


Figure 5. CTR for LDPE and HDPE beads in a 60° inclined hole.

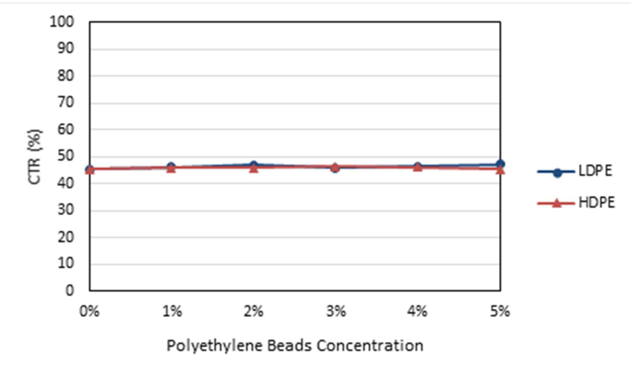


Figure 6. Polyethylene Beads Concentration in a horizontal hole.

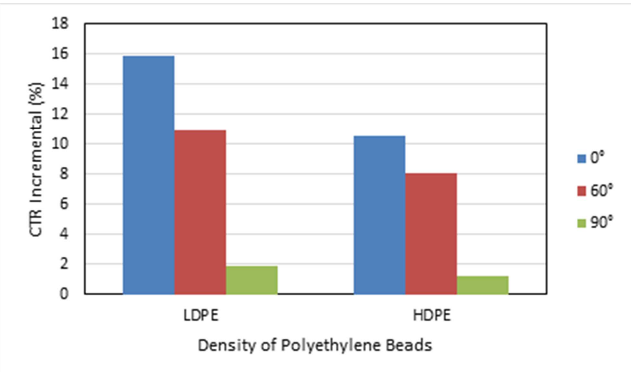


Figure 7. Density of Polyethylene Beads.

3.3. Force Analysis

LDPE and HDPE beads were added to improve cuttings lifting efficiency. Two types of forces; buoyancy and impulsive forces were involved in this mechanism. LDPE performed better than HDPE. Equation (1) clearly illustrates that buoyancy force is directly proportional to volume, meaning when the concentration of beads increase, the impact of buoyancy force becomes higher. On comparison between LDPE and HDPE beads, the LDPE beads have a lower density which results into a higher buoyancy force. LDPE beads experience higher upward velocity than HDPE thus resulting in better hole cleaning as shown in Figure 9. The upward buoyancy force enables LDPE and HDPE beads to travel with a higher velocity in the mud flow stream. However, the resultant force in mud flow direction was reduced by hole inclination. In other words. The buoyancy force of the beads becomes less functional towards a horizontal well.

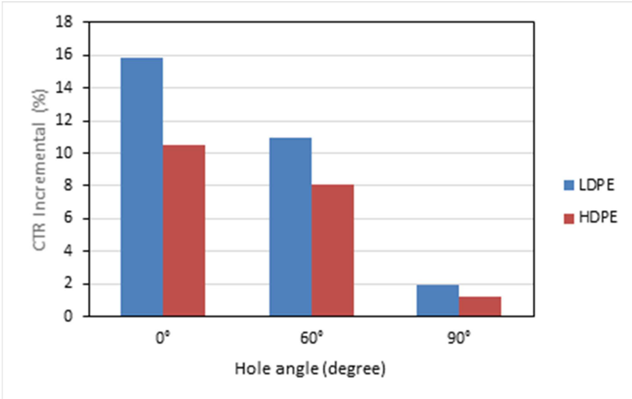


Figure 8. Incremental CTR by LDPE and HDPE beads at different angles.

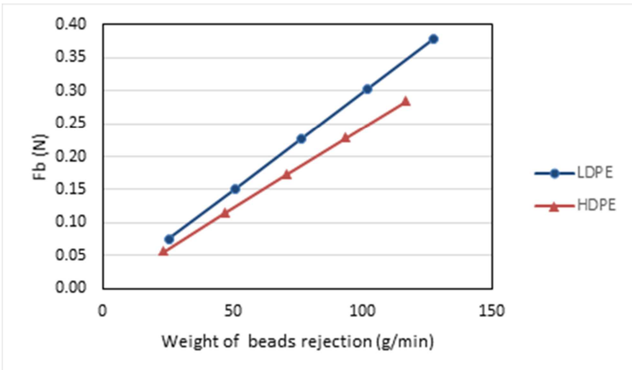


Figure 9. Buoyancy force in LDPE and HDPE beads.

This also indicated the significance of the LDPE beads as well as its improvement on cuttings lifting efficiency as the hole inclination increased. High velocity collisions between LDPE and HDPE beads and the drilled cuttings produced impulsive forces which are able to accelerate the cuttings transport. Tables 5 and 6 show the increase of impulsive force with concentration in LDPE and HDPE beads since more beads increase the frequency of collision. In addition, the impulsive force decreased with a higher hole inclination. Collision between beads and sand cuttings occurred least in a horizontal hole because of the resultant force of buoyancy being negligible in a horizontal well as shown Figure 6, thus uniform travel velocity of beads and cuttings. Secondly, the low dense LDPE beads tend to float on one side of the inclined hole and reduce the collision rate with cuttings.

Table 5. *LDPE Impulsive Force.*

Concentration	Impulsive force (N)		
	0° angle	60° angle	90° angle
1%	0.99	0.66	0
2%	1.58	1.06	0
3%	1.90	1.28	0
4%	2.15	1.44	0
5%	2.44	1.63	0

Table 6. *HDPE Impulsive Force.*

Concentration	Impulsive force (N)		
	0° angle	60° angle	90° angle
1%	0.89	0.66	0
2%	1.44	0.97	0
3%	1.74	1.17	0
4%	1.98	1.33	0
5%	2.26	1.52	0

4. Conclusions

The experimental investigation successfully determined the effects of LDPE and HDPE beads on cutting lifting efficiency in different hole angles. LDPE beads were effective in lifting drilled cuttings in vertical and 60° angled holes than HDPE. In terms of the lifting performance of polyethylene beads in different hole angles, the CTR in a vertical hole gave the best result for both densities. Furthermore, there was no significant lifting in the horizontal hole for both low and high density polyethylene beads. When the concentration of low and high density polyethylene beads was increased, the cuttings transport ratio was higher in every angle except for the horizontal hole. The relationship between the concentration of beads and CTR can be justified using impulsive and buoyancy forces.

Nomenclature

ID	Inner diameter
OD	Outer diameter
GS	Gel Strength
YP	Yield Point
OBM	Oil Based Mud
WBM	Water Based Mud
μ_a	Apparent viscosity
μ_p	Plastic viscosity
PVC	Polyvinyl Chloride
FL	Filtrate Loss Volume
MCT	Mud Cake Thickness
CTR	Cuttings Transport Ratio
LDPE	Low Density Polyethylene Beads
HDPE	High Density Polyethylene Beads

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