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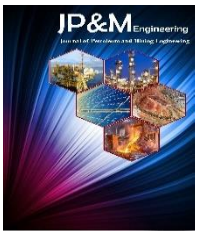

Comprehensive Review on Wellbore Cleaning: Analyzing Factors, Simulation Models and Emerging Technologies for Enhanced Drilling Efficiency

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Abstract

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Inadequate wellbore cleaning is a recurring problem since cuttings removal from thousands of meters downhole to the surface is challenging during any drilling process. High concentrations of cuttings or any drilling fluid residues left at the bottom or at challenging sections of the well could cause formation damage, impede well completion, and damage completion tools. In this work, we comprehensively review past studies related to hole cleaning to provide means that aid in avoiding expensive workover services such as fishing and clean-up procedures. To this end, we aim to systematically examine data on recent hole cleaning flow loop designs and examine the primary outcomes of research centred around the crucial factors influencing borehole cleaning and its simulation modelling. Interrelated impacts of the rheological properties of drilling fluids, flow rate, hole inclination, hole eccentricity, drill pipe rotation, and cutting size in hole cleaning processes are also discussed. Furthermore, this study presents an overview of the various analytical and numerical modelling approaches that are used for hole cleaning analyses. Additionally, the role of artificial intelligence (AI) and machine learning (ML) in predicting the hole cleaning process is discussed. Finally, recommendations for improvements in the hole cleaning process are emphasized to offer insights for guiding future investigations in this area.

Keywords

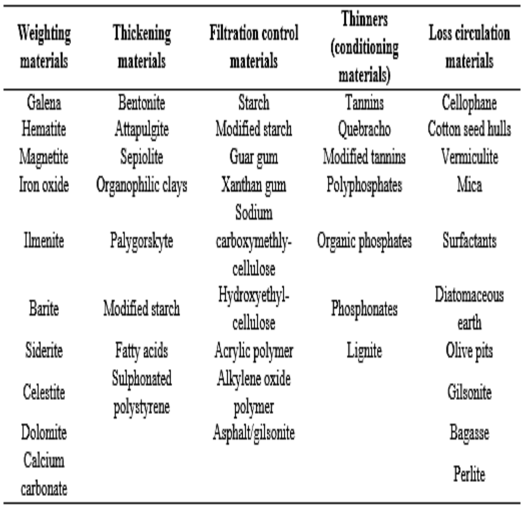
Hole cleaning; Drilling; Rheological properties; Artificial Intelligence

Introduction

Hole cleaning is the process of removing rock fragments or otherwise known as drilled cuttings out of a wellbore and to the surface. Drilling fluid can be defined as a medium that assists in generating and removing cuttings to the surface. The ability of drilling fluid to conduct this process is imperative for a successful drilling operation [1,2]. Carrying capacity or cuttings transport are also terms used to describe hole cleaning.

The drilling fluid is considered as one of the most important aspects in well construction. However, the various additives contained in the drilling fluid may have adverse impacts on the environment. Table 1 shows examples of additives used in the oil and gas industry. Therefore, the formulation of an environmentally friendly drilling fluid is becoming a priority. The awareness concerning the environment pushes the future direction of research works towards focussing on environmentally friendly drilling fluids that are effective and have low cost.

Table 1 Common additives in drilling fluid systems [3,4]



Weighting materials	Thickening materials	Filtration control materials	Thinners (conditioning materials)	Loss circulation materials
Galena	Bentonite	Starch	Tannins	Cellophane
Hematite	Attapulgite	Modified starch	Quebracho	Cotton seed hulls
Magnetite	Sepiolite	Guar gum	Modified tannins	Vermiculite
Iron oxide	Organophilic clays	Xanthan gum	Polyphosphates	Mica
Ilmenite	Palygorskyte	Sodium carboxymethly-cellulose	Organic phosphates	Surfactants
Barite	Modified starch	Hydroxyethyl-cellulose	Phosphonates	Diatomaceous earth
Siderite	Fatty acids	Acrylic polymer	Lignite	Olive pits
Celestite	Sulphonated polystyrene	Alkylene oxide polymer		Gilsonite
Dolomite		Asphalt/gilsonite		Bagasse
Calcium carbonate				Perlite

One of the most important attributes of drilling fluid is to avoid the accumulation of cuttings at the bottom of the wellbore by effectively removing cuttings. This is to ensure the wellbore is as clean as possible to prevent problems such as pipe sticking and to allow the drilling fluid to circulate efficiently while drilling. According to Bourgoyne et al. (1991) [5], apart from transporting cuttings to the surface, drilling fluids have other functions such as reducing formation damage, controlling formation pressures, and reducing torque and drag, among others.

When a well is drilled, drilled cuttings that are not successfully transported out of the wellbore will cause well problems such as pipe sticking, decreased rate of penetration, formation fracturing, and many others [6]. Figure 1 shows the potential problems that may occur in directional drilling. In such instances, the accumulation of cuttings especially at critical angles will not only be costly but will also drag out the operation time or increase non-productive time (NPT). According to Forshaw et al. (2020) [7], up to 30% of the upstream costs in oil and gas production is due to NPT, and half of this is attributed to downhole drilling problems where hole cleaning is the prominent cause for the loss of tens of millions of dollars due to lost time. The chances of a successful hole cleaning decrease when drilling in complex structural wells. These types of wells are usually highly inclined wells or high-pressure high-temperature (HPHT) wells or both.

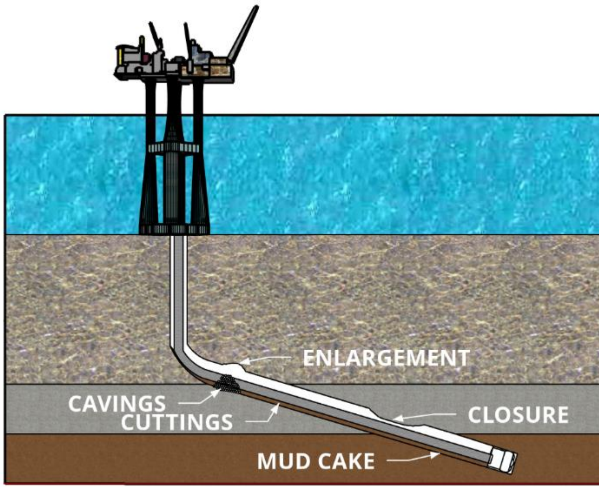


Figure 1 Potential problems in directional drilling operations (adopted from Rasi, 1994 [8])

Inadequate cuttings transport is a complex problem, especially in horizontal or highly inclined wellbores. The reason for the complexity associated with inadequate cuttings transport is that it is affected by many parameters in varying degrees and not all of them are measurable and fully understood [9]. The cuttings transport performance during drilling operations depends on factors such as fluid flow regime, hole inclination and geometry, drill pipe rotation, pipe eccentricity, average fluid velocity, drilling fluid rheological properties, cuttings size and shape, and rate of penetration [10-13].

In the literature, there have been extensive series of laboratory tests focused on several key factors that affect hole cleaning. Okrajni and Azar (1986) [14] and Brown et al. (1989) [15] investigated the effects of fluid rheology, flow rate, hole inclination angle, and drill pipe geometry on hole cleaning performances. Both studies compared the performance of water- and polymer-based fluids in annular hole cleaning for deviated wells. Okrajni and Azar (1986) [14] also included the effects of drillpipe rotation in their study while Brown et al. (1989) [15] complemented their findings by including mathematical modelling for cutting transport. Apart from that, Peden et al. (1990) [11], Sifferman and Becker (1992) [16], and Martins et al. (1996) [17] not only studied the effects of fluid rheology, flow rate, hole inclination angle, and drillpipe geometry but also the cuttings size. Peden et al. (1990) [11] found that the biggest impact on the minimum transport velocity is associated with fluid rheology and flow rate, while Sifferman and Becker (1992) [16] reported that fluid rheology and fluid density have the greatest effect on hole cleaning. On the other hand, Martins et al. (1996) [17] developed a group of correlations to predict the cuttings bed height, and the critical flow rate required to erode cuttings bed deposited on the lower part of a horizontal wellbore.

To better understand the key factors influencing the removal of cuttings, this study provides an updated and extensive review of hole cleaning studies. In the next sections, we comprehensively review recent hole cleaning studies which include experimental, analytical, and numerical simulation research investigations. Such review helps to improve our understanding of the mechanisms involved in the hole cleaning process and highlights the challenges and key areas that require further research.

Experimental studies on the hole cleaning process

The process of carrying out a dynamic experimental study on hole cleaning requires detailed planning, management, and proper execution. Risk analysis should also be considered in the early stages of the research. A great emphasis needs to be placed on determining the suitable range of parameters that affect hole cleaning such as the type of drilling fluid to be studied and its velocity profile, flow rate, cuttings size, hole inclination angle, among others.

Flow loop designs

The key factors that affect hole cleaning and those that require further attention in experimental research should be identified to be able to design and fabricate an experimental flow loop to accurately control and simulate real conditions. Past hole cleaning experimental flow loops were designed to study the build-up of solids in the test section [18-29]. This is otherwise known as solid distribution tests where cuttings are circulated into the test section and bedding phenomena are investigated in the annulus [30]. In these studies, pressure drops, trapped cuttings volume, fluid and gas volumes are measured and analyzed. Furthermore, in some of these studies, transparent sections are designed to study the flow patterns observed.

Sunthankar et al. (2000) [18] attempted to better understand aerated mud hydraulics (air and aqueous polymer solution) to calculate bottom hole pressure and optimal flow rates for drilling. They measured pressure and liquid holdup over the entire annular section and found that the effect of drillpipe motion on frictional pressure drops was mainly associated with the lateral motion (instead of rotational) and the turbulence it causes, besides the shear-thinning effect for the air-aqueous polymer solution flow.

Later, Naganawa et al. (2002) [21] studied cuttings transport by aerated fluids in directional and horizontal wells. The key factors analyzed were hole inclination angle of 30° to 90° from the vertical direction, fluid rheology of water and partially hydrolyzed polyacrylamide polymer (PHPA) solution, hole geometry (concentric and eccentric annulus), and volumetric concentration of cuttings in the annulus. A significant reduction in the critical flow rate and improvement in the cuttings transport efficiency were observed in highly inclined annuli when the air was injected into the system. However, at horizontal sections, relying on air injection alone was insufficient as an annular velocity of 1.5 m/s was still required for effective cuttings transport.

Meanwhile, Kelessidis and Mpandelis (2003) [22] studied the effects of flow patterns and minimum suspension velocity in horizontal and deviated coiled-tubing drilling for efficient hole cleaning. Key parameters tested were flow rate, hole inclination angle, and fluid density in the concentric and eccentric annuli. They found that turbulent flow is the best flow regime for cutting transportation. Other than that, Ozbayoglu et al. (2003) [23] experimentally investigated a broad range of annular velocities, cuttings injection rates, and hole inclination angles, 70° to 90° from the vertical direction, using foam qualities of 70% to 90% and found that foam behaves as a pseudoplastic fluid and noticeable wall slip occurred when using 80% and 90% foam qualities. They managed to develop a three-layer model to solve equations for flow velocities, cutting bed height, slip velocity, the concentration of cuttings and pressure drop using their experimental results. A few years later, using the same flow loop system, Duan et al. (2006) [25] studied the main factors affecting small cuttings transport by comparing the effects of cuttings size, drillpipe rotation, fluid rheology, flow rate, and hole inclination. They developed correlations to obtain cuttings concentration and bed height in an annulus using mathematical modelling with errors mostly within 10% of the experimental results.

Additionally, Zhou et al. (2004) [24] and Chen et al. (2007) [26] configured an advanced experimental flow loop that was used to simulate downhole conditions at elevated pressures and temperatures. Zhou et al. (2004) [24] investigated the effects of aerated mud in the horizontal wellbore and the test parameters were liquid and gas flow rates, cuttings weight in the annulus, liquid holdup, mixture density, and pressure losses. Their findings stated that the effects of an increase in pressure on cutting concentration are minimal. Chen et al. (2007) [26] on the other hand, analyzed the effects of polymer additives, foam quality, flow velocity, temperature, and pressure on foam cuttings transport in the horizontal annulus. The results of their study showed that low-quality foams of 70% and 80% needed higher critical velocities compared to high-quality foams (90%).

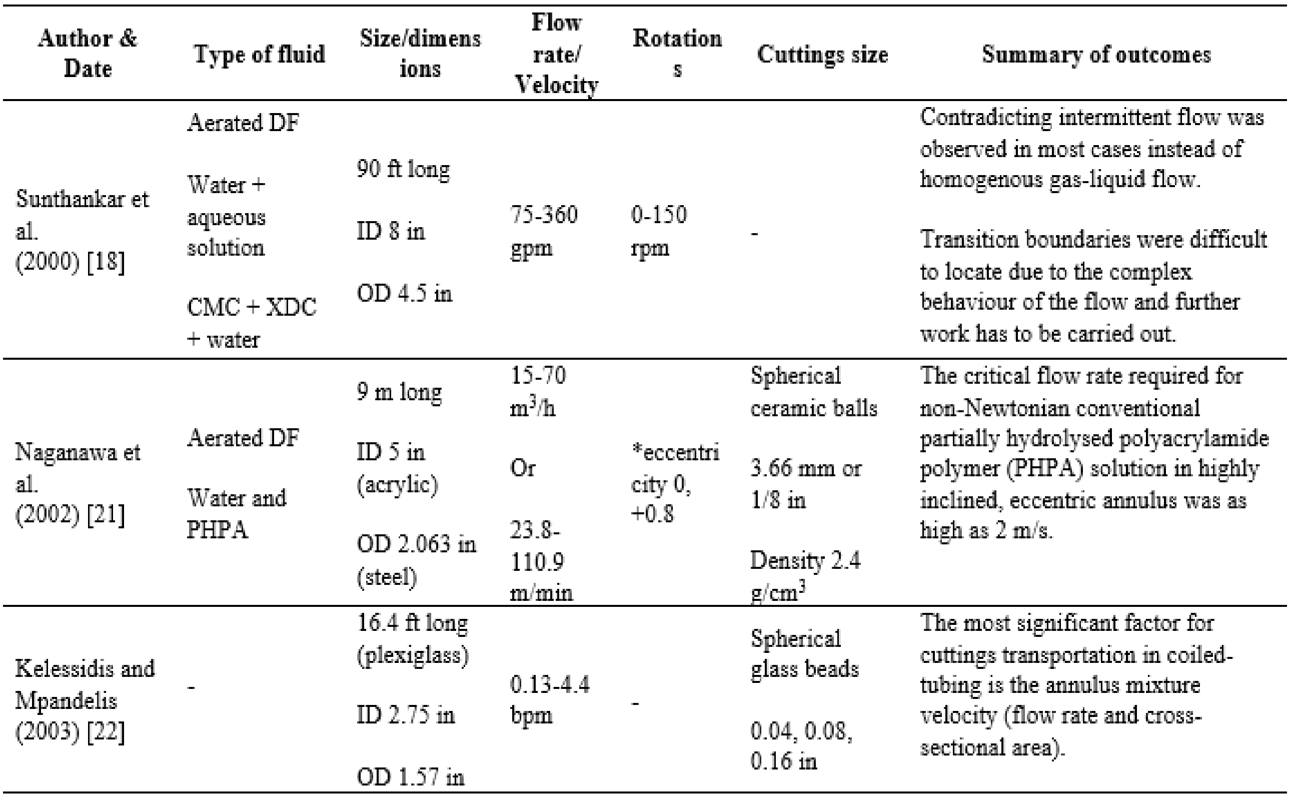
Afterwards, more studies were conducted with improvised flow loop systems. For example, Ozbayoglu et al. (2008) [27], Ozbayoglu et al. (2010) [28], and Gul et al. (2017) [29] included a flow loop system with a transparent simulated casing (test section) to observe different flow regimes, cuttings movements and bed development. Ozbayoglu et al. (2008) [27] investigated the effect of pipe rotation on hole cleaning using water-based drilling fluids while varying other key parameters such as hole inclination angle (50° to 90° from vertical direction), rate of penetration, and flow velocity. They found that as fluid viscosity increases, the contribution of pipe rotation on hole cleaning also increases when compared to cases with no rotations. Ozbayoglu et al. (2010) [28] conducted an experimental study to remove cuttings bed in horizontal and deviated wells using water to demonstrate light drilling fluid flow conditions. They complimented their findings with easy-to-use empirical correlations to estimate critical fluid velocity required to prevent bed development with reasonable accuracy. Gul et al. (2017) [29] investigated the effects of aerated fluids (air-water and air-drag reducing polymer mixtures) with different rheological characteristics on cutting transport efficiency. The air-drag reducing polymer mixture was able to reduce drag for cuttings transport by 23.9%, cuttings concentration in the annulus by 4%, and cuttings bed height by 13.78%.

Table 2 shows the details of the experimental flow loop designs including the main outcomes from each study. Further discussions and comparisons of the key factors affecting hole cleaning are explained in the next section.

Furthermore, Boyou et al., 2019 investigated nano-enhanced water-based mud in directional drilling for hole cleaning. Key parameters in their study were hole inclination angle, drillpipe rotation, cuttings size, and rheological properties. The key takeaway from this study was that nanosilica improved cuttings transportation efficiencies in all inclination angles and further improvements were recorded when pipe rotation of 150 rpm was applied.

Finally, recent hole cleaning studies were also carried out to investigate the effects of polymer beads on cuttings transport. These experimental studies included an added separation section in the design of their experimental rig to separate polymer beads from the drilling fluid as well as cuttings flowing in the system. Onuoha et al. (2015) [31] and Boyou et al. (2018) [32] investigated the effect of various concentrations of polypropylene (PP) beads on hole cleaning at various hole inclination angles. Heshamudin et al. (2019) [33] also carried out the same study and included the effects of drillpipe rotation. Other than the use of polypropylene beads (PP) beads for hole cleaning improvement using water-based mud, the effect of polyethylene (PE) polymer beads was also investigated. Yeu et al. (2018) [34] studied the effect of low-density polyethylene (PE) beads at different mud circulation rates at different hole angles. Yi et al. (2017) [35] investigated low- and high-density polyethylene (PE) beads in concentrations ranging from 1% to 5% by volume in transporting various cuttings sizes at hole inclination angles 0° to 90° from vertical. Furthermore, Hakim et al. 2018 [36] compared the effects of different concentrations of polypropylene (PP) and polyethylene (PE) polymer beads in transporting various cuttings sizes in the horizontal wellbore.

Table 2 Experimental flow loops that were used for the hole cleaning tests.



Author & Date	Type of fluid	Size/dimensions	Flow rate/ Velocity	Rotations	Cuttings size	Summary of outcomes
Sunthankar et al. (2000) [18]	Aerated DF Water + aqueous solution CMC + XDC + water	90 ft long ID 8 in OD 4.5 in	75-360 gpm	0-150 rpm	-	Contradicting intermittent flow was observed in most cases instead of homogenous gas-liquid flow. Transition boundaries were difficult to locate due to the complex behaviour of the flow and further work has to be carried out.
Naganawa et al. (2002) [21]	Aerated DF Water and PHPA	9 m long ID 5 in (acrylic) OD 2.063 in (steel)	15-70 m^3/h Or 23.8-110.9 m/min	*eccentricity 0, +0.8	Spherical ceramic balls 3.66 mm or 1/8 in Density 2.4 g/cm^3	The critical flow rate required for non-Newtonian conventional partially hydrolysed polyacrylamide polymer (PHPA) solution in highly inclined, eccentric annulus was as high as 2 m/s.
Kelessidis and Mpandelis (2003) [22]	-	16.4 ft long (plexiglass) ID 2.75 in OD 1.57 in	0.13-4.4 bpm	-	Spherical glass beads 0.04, 0.08, 0.16 in	The most significant factor for cuttings transportation in coiled-tubing is the annulus mixture velocity (flow rate and cross-sectional area).

Ozbayoglu et al. (2003) [23]	Foam	100 ft long ID 8 in (3/4 in. wall thickness) OD 4.5 in (aluminium alloy pipe)	2-18 ft/s	-	-	Bed thickness increases with the increase in foam qualities at a given flow rate and rate of penetration. Hole inclination of 70° to 90° had little effect on cuttings transport with foam.
Zhou et al. (2004) [24]	Aerated fluids (Air + water)	73 ft long ID 6 in OD 3.5 in	80-150 gal/min Gas liquid ratio (0-0.38)	-	Average 0.118 in (3 mm) Density 2610 kg/m^3) porosity 38%	Experimental results and model predictions show a significant increase of cuttings concentration in the annulus at given flow conditions as temperature increases.
Duan et al. (2006) [25]	Water + polyanionic cellulose (PAC)	100 ft long ID 8 in OD 4.5 in	200-400 gpm	0-80 rpm *eccentricity of 0.8	0.45, 1.4, and 3.3 mm	Pipe rotation and fluid rheology were the main factors contributing to small cuttings transport. More viscous fluid significantly enhances the transport of smaller cuttings but not larger cuttings. The transport of larger cuttings is dominated by the fluid flow rate.
Chen et al. (2007) [26]	Foam surfactant (1% v/v) Hydroxyl-ethylcellulose Polymer (HEC), (0.0, 0.25, and 0.5% v/v)	73 ft long ID 5.76 in OD 3.5 in	2-6 ft/s	Max 250 rpm	-	There were only slight changes in cuttings transport concentrations at elevated pressure and temperature conditions which is a desirable property of foam.
Ozbayoglu et al. (2008) [27]	Water Water-based mud	12 ft long ID 3 in OD 1.5 in	2.1 to 7.2 ft/s	0 – 120 rpm	-	Pipe rotation drastically reduces the fluid velocity required to completely remove stationary cuttings bed.
Ozbayoglu et al. (2010) [28]	Water	15 ft long ID 4 in OD 2 in	40-250 gpm	-	-	The dimensional analysis showed that shear stress acting on the cuttings on bed surface was the major variable influencing cuttings bed thickness.
Onuoha et al. (2015) [31]	Water-based mud with polypropylene (PP) beads	13 ft long ID 2 in (acrylic pipe) OD 0.79 in	2.1 ft/s (0.64 m/s)	-	1.0 to 1.2 mm (irregular shape) Density of 2.4 g/cc	Polypropylene (PP) beads contributed more significant improvement in cuttings transport efficiency in the vertical hole compared to a highly deviated or horizontal hole.

Gul et al. (2017) [29]	Aerated DF Polymer fluid Partially hydrolysed polyacrylamide (PHPA) copolymer	21 ft long ID 2.91 in OD 1.85 in	35-100 gpm	-	2.75mm	Partially hydrolysed polyacrylamide (PHPA) in water delayed the flow regime transition from slug to annular wavy
Yi et al. (2017) [35]	Water-based mud with (1% to 5%) low and high-density polyethylene beads	11 ft long ID 1.80 in (Polyvinyl chloride pipe) OD 0.85 in	0.8 m/s	-	1.18 to 2.00 mm Density of 2.65 g/cc	The collision between polyethylene (PE) beads and cuttings introduced impulsive force which enabled the cuttings to be transported more efficiently.
Boyou et al. (2018) [32]	Water-based mud with (1% by weight) polypropylene beads	4m long ID 51 mm OD 20 mm	0.78 m/s	-	0.50 to 3.34 mm	Polypropylene beads (PP) beads showed an overall positive effect in improving cuttings transport efficiency however, the improvement reduced as the drilled cuttings sizes approached or were close to the size of polymer beads.
Yeu et al. (2018) [34]	Water-based mud with (1% to 5%) low-density polyethylene beads	11 ft long ID 45.6 mm (Polyvinyl chloride pipe)	0.4, 0.6, 1.0 L/s	-	1.18 to 2.00 mm Density of 2.66 g/cc	The effect of low-density polyethylene beads on cuttings transport was magnified at high flow rates due to the even distribution of beads and cuttings in the annulus, which induced higher impulsive force.
		OD 12.6 mm				
Hakim et al. 2018 [36]	Water-based mud with 1%–5% by vol. Concentrations of polyethylene (PE) and polypropylene (PP) polymer beads	13 ft long ID 2 in (acrylic pipe) OD 0.79 in (PVC pipe)	0.69 m/s	-	0.5-4 mm	Polypropylene (PP) beads performed better than polyethylene (PE) beads due to its lower density.
Boyou et al. 2019 [37]	Water-based mud with nanosilica	20 ft long ID 2.75 in OD 1.05 in	4.7 ft/s	0 and 150 rpm	1.4 to 4mm	Easy dispersion of hydrophilic nanosilica was reported by increasing the pH level of water to 12.6. Nanaosilica enhanced water-based mud was able to increase the colloidal interaction with cuttings and contributed 30.8% to 44% cuttings transport efficiency improvement.
Heshamudin et al. (2019) [33]	Water-based mud with (2-8 ppb) polypropylene beads	13 ft long ID 2 in OD 0.8 in	3.48 m/s	0 to 150 rpm	0.5 to 2.0 mm Density 2400 kg/m3	The effect of polypropylene beads in horizontal sections are not prominent however when pipe rotation was present, cuttings transport efficiency improves significantly.

All these studies concluded that polymer beads introduce buoyant force to counteract gravitational force acting on cuttings which improve cuttings transport efficiency.

A more detailed elaboration of the findings is discussed later in this manuscript. In these studies, cutting transport efficiency (CTE) is calculated using the following equation:

$$CTE = \frac{Weight\ of\ recovered\ drilled\ cuttings}{Initial\ weight\ of\ injected\ drilled\ cuttings} \times 100\% \qquad (1)$$

Impact of drilling fluid properties on hole cleaning

Factors affecting hole cleaning are interrelated to each other. This is because when cuttings travel through the annulus during drilling, the mud rheology, flow rate, hole inclination especially at critical angles, pipe eccentricity and pipe rotation all play a key role in determining the transport ratio of cuttings. When any one of these factors changes, the rate of transport of cuttings will change too. Thus, it is important to study how all these factors could affect fluid dynamics in the well and hole cleaning performance.

Rheological properties and flow mechanisms

One of the earliest studies on cuttings transport was conducted by Hall et al. (1950) [38]. They stated that one of the most crucial functions of drilling fluid is to remove cuttings and sloughs from the wellbore to avoid challenges that come with insufficient hole cleaning. Later, Peden et al. (1990) [11] stated that water was the best fluid for hole cleaning in small annuli because of the cuttings rolling mechanism, followed by the high viscosity fluids, and the least effective being the medium viscosity fluids. However, in terms of hole cleaning by cuttings suspension, high viscosity fluids are proven to be more effective followed by the low and the medium viscosity fluids, respectively. A study by Brown et al. (1989) [15], mentioned that viscous hydroxyethyl cellulose (HEC) based drilling fluid required lower flow velocities compared to water to initiate the movement of cuttings at hole angles close to vertical. However, as the hole angle increases to 30° from the vertical direction, the hole cleaning is initiated at lower flow velocities with water compared to the viscous HEC fluid. Therefore, different drilling fluids are required for cleanout and drilling operations; less viscous fluids such as water perform better than more viscous fluids such as polymer solutions for cuttings bed erosion, however, polymer solutions perform better than water in preventing bed formation [39]. Peden et al. (1990) [11] concluded that overall, hole cleaning performance worsens when the viscosity of drilling fluid increases due to the transition of flow from turbulent to laminar which deteriorates the performance of fluid to clean the wellbore and that turbulent flow regime has a significant effect on the hole cleaning process. Walker & Li (2000) [19] supported that a low-viscosity fluid in turbulent flow is the best way to lift cuttings out of the borehole and a gel or a multiphase system should be used to maximize the carrying capacity. This claim was further strengthened by Piroozian et al. (2012) [40] where they found cuttings transport improvement by 8% at all angles when fluid viscosity increased; provided that the flow velocity was kept constant, and the flow regime remained turbulent.

According to Okrajni & Azar (1986) [14], yield value and YP/PV ratio do not affect cuttings transport efficiency when the flow is turbulent. However, under laminar flow, the higher the mud yield or YP/PV ratio, the lower the concentration of cuttings in the annulus. Sifferman & Becker (1992) [16] adds to the discussion that when a drillpipe is stationary, a decrease in rheological properties of the mud causes a decrease in cuttings bed, while rheology has less effect when drillpipe rotation is at 60 rpm. Sanchez et al. (1997) [41] also added that for thinner muds (PV/YP=7/7), the concentration of cuttings in the annulus was higher for smaller cuttings compared to larger ones. However, when a thicker mud (PV/YP=20/20) was used, the difference in the concentration of the two sizes was less. This proves that the buildup of cuttings in the annulus not only depends on the rheological properties of the drilling fluid but also the knowledge of flow behaviour (turbulent or laminar flow), the presence of drillpipe rotation, and the size of cuttings.

Over the years, studies on improving the rheological properties of drilling fluid heightened as new additives and new fluids started to emerge. Gul et al. (2017) [29] noticed a maximum drag reduction of 41.88% when polymer fluid with an optimum partially hydrolysed polyacrylamide (PHPA) concentration of 0.07% V/V was used. Naganawa et al. (2002) [21] also noticed that the critical flow rate for aerated Newtonian fluid (water) was lower than base liquid (PHPA solution) in low inclined and horizontal annuli. However, in highly inclined annuli, the critical flow rate for aerated fluid was slightly higher than that for the base liquid. Apart from that, a different study done by Duan et al. (2006) [25] found that adding 0.25 ppb of polyanionic cellulose (PAC) showed rheological properties improvement to where it significantly improves small cuttings transport but only slightly improves large cuttings transport. According to Ozbayoglu et al. (2003) [23], foam qualities of 80 and 90% exhibited noticeable wall slip and foam behaved as pseudoplastic fluid. Furthermore, adding HEC-polymer to the foam system was proven to be beneficial for hole cleaning however it also increases frictional pressure loss. Thus, proper design of hydraulics of polymer foam is imperative in planning foam drilling operations [26]. A recent study conducted by Boyou et al. (2019) [37] stated that the addition of nanosilica in water-based mud showed a reduction in the apparent viscosity, plastic viscosity, yield point, and gel strength (Figure 2). This is especially important for high mud weights in which such additives reduce the required pump pressure during drilling without compromising sufficient rheological properties for cuttings removal.

Other research also suggests that adding polymer beads to drilling fluids showed beneficial results. According to Onuoha et al. (2015) [31], the presence of 1.5% concentration of polypropylene beads in drilling mud was able to improve cuttings transport performance by more than 10%. Meanwhile, Boyou et al. (2018) [32] recorded that polypropylene beads were able to improve cuttings transport efficiency by 4 to 8% depending on hole inclination. Different polymer beads, polyethylene beads, were studied by Yi et al. (2017) [35] and they reported improvements in the cuttings transport efficiency by more than 15%. Yeu et al. (2018) [34] added that as the concentration of low-density polyethylene beads increased, cuttings transportation also increased. Also, Hakim et al. (2018) [36] reported that as the concentration of polyethylene and polypropylene beads increased from 1% to 5%, the cuttings transport efficiency increased from 55% and 63% to 90% and 95%, respectively. Hole cleaning experiment done by Heshamudin et al. (2019) [33] concluded that the cuttings transport ratio increased and reached its highest level as the concentration of polypropylene beads was 8 ppb in water-based mud. A review study that was done by Mahmoud et al. (2019) [42] compared some of the hole cleaning findings using polymer beads and base muds (Figure 3). The results showed that the highest improvement at horizontal inclination, which was 15%, could be achieved by adding polypropylene beads [36]. Moreover, Polymer beads were able to increase drag force by directing cuttings to the direction of mudflow. For example, Skalle (2011) [43] and Peden et al. (1990) [11], the forces acting on a cutting in motion in a deviated well, are the gravitational forces (Fg), drag forces (Fd), friction forces (Ff), and cohesive forces (Fc) as shown in Figure 4. Yi et al. (2017) [35], Boyou et al. (2018) [32], and Yeu et al. (2018) [34] concluded that polymer beads were able to provide sufficient buoyancy force to counteract gravitational force and reduce slip velocity of cuttings due to their lower density. When this happens, lift, and drag forces increase which produces better cuttings transport performance. Yeu et al. (2018) [34] also found that increasing the concentration of polymer beads causes a higher frequency of collisions with cuttings which increases impulsive forces. However, based on these studies, caution should be considered on the concentration of polymer beads added into the system because a high concentration of polymer beads increases the number of solid particles in the annulus, and this could be detrimental in drilling operations. Yet, there is no report on the maximum allowable polymer concentration to avoid excessive concentrations of polymer beads in the annulus.

It should be noted that it is important to understand drilling fluid’s behavioural changes as different additives are incorporated to improve rheological properties for better performance, however, determining the pressure loss rate is also important for drilling fluid design and that solely relying on viscosity parameters should be avoided [44]. Chen et al. (2007) [26] reported that adding hydroxyethyl cellulose polymer (HEC) as viscosifier to foam systems decreases the cuttings concentration in the annulus and increases frictional pressure losses. Shigemi (2002) [45] and Gul et al. (2017) [29] however, concluded that the use of partially hydrolysed polyacrylamide (PHPA) copolymer in aerated fluids decreases frictional pressure losses and cuttings concentrations in the annulus. Other researchers such as Kang and Jepson (2000) [46], Al-Sarkhi et al. (2006) [47], and Hamouda (2013) [48] found that polymeric additives or drag reducers are very effective in reducing pressure losses in two-phase flows in annular configurations but the effectiveness varies depending on fluid type and wellbore configuration. Some of the key findings on the effect of rheology and flow mechanism on hole cleaning are tabulated in Table 3.

Apart from investigating the performance of drilling fluid dynamically, in flow loop setups; improving rheological properties of drilling fluids by incorporating nanomaterials in static tests has also been studied closely as preliminary analysis to improve hole cleaning. There have been several investigations into the use of nanomaterials to modify drilling fluid performance, which have shown promising results. Plastic viscosity, yield point, and gel strength are often the key parameters that dictate the performance of drilling fluid in terms of rheology. Nanomaterials are known to improve the viscosity of drilling fluid (in most cases), and the improvements depend on the type of mud, and the type, size as well as concentration of nanomaterials added. Caution should be applied because if the viscosity is too high, the drilling fluid is not able to drill rapidly as the high viscosity of drilling fluid exiting at the bit causes resistance to flow. On the other hand, the yield point is the stress required to initiate a flow or fluid movement. The higher the yield point, the higher the ability of the mud to lift cuttings. In some cases, as mentioned in Table 4, nanoparticles were not able to increase or maintain high yield point, therefore, it is wise to add other additives such as deflocculants or chemical modifiers to reduce attractive forces between particles. Gel strength is one of the most important factors in maintaining a good drilling fluid rheology because it expresses the ability of the drilling fluid to suspend drill cuttings and weighing materials when drilling fluid is in static condition. Usually, low, and non-progressive gel strengths are required for optimum performance. Table 4 shows the effect of different types of nanomaterials on rheological properties.

Deep wells and hostile environments often degrade traditional drilling fluids; thus they lose their capability to function properly throughout the drilling process. According to Abdo & Haneef (2010) [49], a decrease in viscosity due to the breakage or association of the polymer chains and branches by temperature variation can be dealt with using nanomaterials because of their capability of having good thermal conductivity. Table 5 shows previous studies of nanomaterials' impact on the thermal stability of drilling fluid.

Based on the key findings tabulated in Tables 5 and 6, not all types of nanomaterials contributed to favorable modifications in the rheological properties of the drilling fluids. The availability and cost of nanomaterials should also be a major factor when developing new and improved drilling fluids, as the price of the drilling operation could increase significantly.

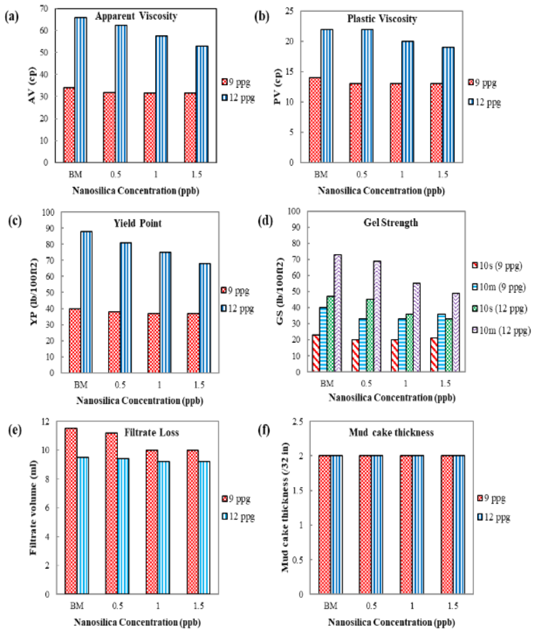


Figure 2 Rheological properties and filtrate losses of 9 and 12 ppg drilling fluids with different concentrations of nanosilica (adopted from Boyou et al., 2019 [37])

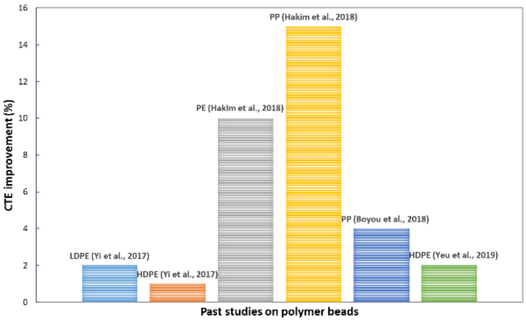


Figure 3 Comparison of cuttings transport efficiency improvement using polymer beads in horizontal inclinations (adopted from Mahmoud et al., 2019 [42])

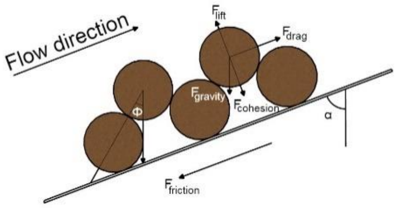
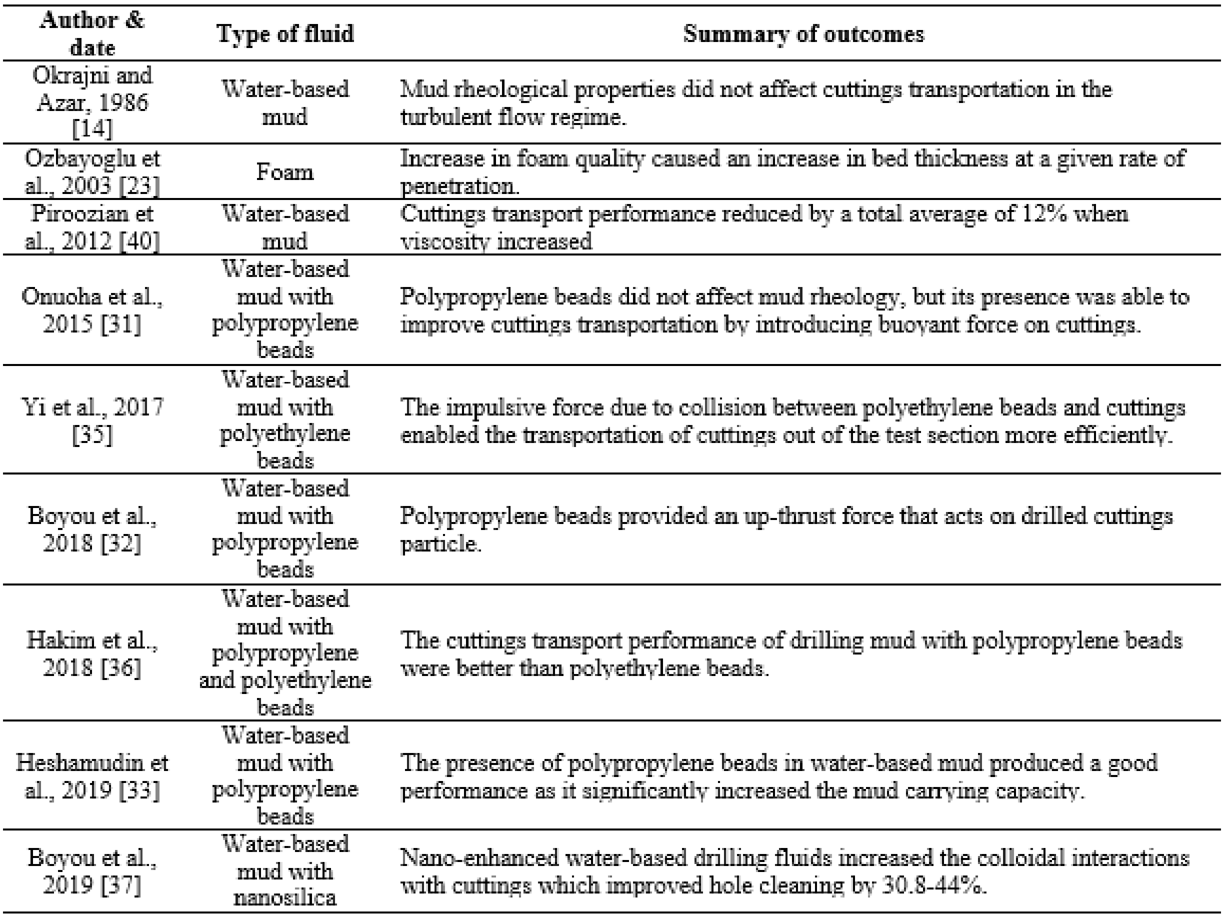


Figure 4 Forces acting on the particle at an active erosion site of a cuttings bed (adopted from Skalle, 2011 [43])

Table 3 Main findings of the effect of drilling fluid formulation and rheological properties on

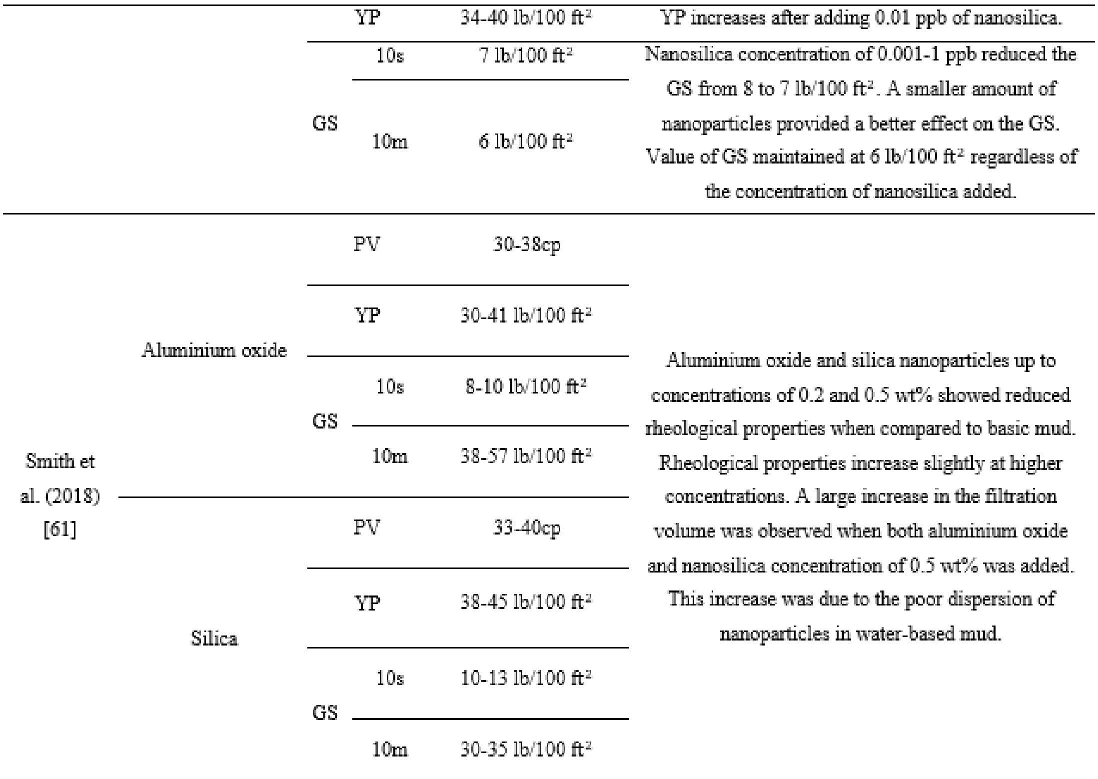


Author & date	Type of fluid	Summary of outcomes
Okrajni and Azar, 1986 [14]	Water-based mud	Mud rheological properties did not affect cuttings transportation in the turbulent flow regime.
Ozbayoglu et al., 2003 [23]	Foam	Increase in foam quality caused an increase in bed thickness at a given rate of penetration.
Piroozian et al., 2012 [40]	Water-based mud	Cuttings transport performance reduced by a total average of 12% when viscosity increased
Onuoha et al., 2015 [31]	Water-based mud with polypropylene beads	Polypropylene beads did not affect mud rheology, but its presence was able to improve cuttings transportation by introducing buoyant force on cuttings.
Yi et al., 2017 [35]	Water-based mud with polyethylene beads	The impulsive force due to collision between polyethylene beads and cuttings enabled the transportation of cuttings out of the test section more efficiently.
Boyou et al., 2018 [32]	Water-based mud with polypropylene beads	Polypropylene beads provided an up-thrust force that acts on drilled cuttings particle.
Hakim et al., 2018 [36]	Water-based mud with polypropylene and polyethylene beads	The cuttings transport performance of drilling mud with polypropylene beads were better than polyethylene beads.
Heshamudin et al., 2019 [33]	Water-based mud with polypropylene beads	The presence of polypropylene beads in water-based mud produced a good performance as it significantly increased the mud carrying capacity.
Boyou et al., 2019 [37]	Water-based mud with nanosilica	Nano-enhanced water-based drilling fluids increased the colloidal interactions with cuttings which improved hole cleaning by 30.8-44%.

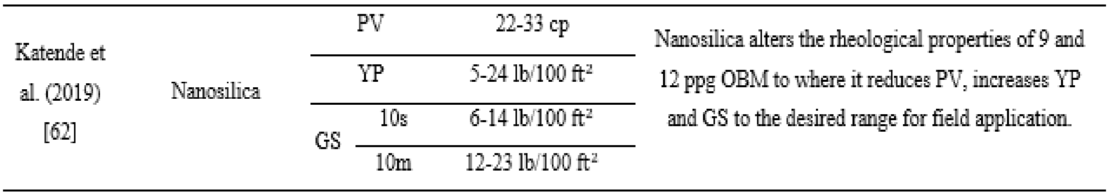
Table 4 Summary of the effect of nanomaterials on rheological properties of drilling fluids

Authors (year)	Type of nanomaterials	Factor/s		Value	Summary of outcomes
Samsuri & Hamzah (2011) [53]	Multi-walled carbon nanotube (MWCNT)	AV		19-22 cp	MWCMT improves the viscosity and displays good stability because surface forces balance the gravity forces which aided cuttings lifting.
Abdo & Haneef (2012) [54]	Attenuated Total Reflectance (ATR)	PV		4 cp	The viscosity increased after ATR (30nm in diameter) were added.
		YP		1 lb/100 ft^2	YP remain constant even after nanoparticles were added.
		GS	10s	1.5 lb/100 ft^2	Displayed high gelling characteristics (improvement of 200%). Result also showed that ATR can also be used in very low shear rates or sluggish conditions due to its low shear stress characteristics.
			10m	4.5 lb/100 ft^2	
Nasser *et al.* (2013) [55]	Nano bentonite	Viscosity		≈ 10 Ns m^{-2}	The viscosity increased after nano bentonite was added.
Abdo & Haneef (2013) [56]	Palygorskite (Pal)	PV		11 cp	The plastic viscosity increased as the particle size distribution of PAL was reduced.
		YP		7.5-8 lb/100 ft^2	The samples lack in maintaining high yield point values thus it is recommended to use a small composition of PAL in the presence of Montmorillonite (Mt) to form thick drilling fluids.
		GS	10s	1.5 lb/100 ft^2	The samples displayed an improvement of 200% of gelling characteristics which makes PAL a superior agent to tackle hole cleaning problems.
			10m	4.5 lb/100 ft^2	
Zawrah *et al.* (2014) [57]	Aluminium oxide	Viscosity		-	Nanofluids with higher concentrations of particles show shear-thinning behaviour but at a lower concentration, neglected effect of shear rate on viscosity.
Ismail *et al.* (2014) [58]	Multi-walled carbon nanotube (MWCNT)	PV		24-36cp	
		YP		18-23 lb/100 ft^2	

		GS	10s	3.8-5.8 lb/100 ft^2	Higher plastic viscosity, yield point and gel strength were observed when the concentration of MWCNT and aluminium oxide nanoparticles increased.
			10m	4.2-7.6 lb/100 ft^2	
	Aluminium oxide	PV		21-29cp	
		YP		19-26 lb/100 ft^2	
		GS	10s	3.2-5.5 lb/100 ft^2	
			10m	3.5-6.5 lb/100 ft^2	
	Titanium oxide	PV		23-25cp	The decrease in plastic viscosity, yield point, and gel strength was observed when the concentration of titanium oxide and copper oxide increased.
		YP		21-18 lb/100 ft^2	
		GS	10s	3.5-3.1 lb/100 ft^2	
			10m	3.1-3.6 lb/100 ft^2	
	Copper oxide	PV		14-24cp	
		YP		7-13 lb/100 ft^2	
		GS	10s	1.5-3.2 lb/100 ft^2	
			10m	2-3.7 lb/100 ft^2	
Mao *et al.* (2015) [59]	Polymer-Based Nanosilica Composite with Core-shell (SDFL)	AV		32 mPa s	As the concentration of SDFL increased, the AV, PV, and YP increased after hot rolling at 230 °C. This means that the drilling fluid shear diluted characteristics became better as well as the improvement in drilling fluid thixotropy. Thus, it is ideal for breaking rock effectively at a high shear rate and suspending cuttings effectively at low shear rate.
		PV		21 mPa s	
		YP		11 Pa	
Ismail *et al.* (2016) [60]	Multi-walled carbon nanotube (MWCNT)	PV		20-22 cp	No significant impact on PV due to small concentrations (0.001 – 0.2 ppb) of MWCNT.
		YP		35-40 lb/100 ft^2	YP increases after adding 0.01 ppb of MWCNT. MWCNT performed slightly better compared to nanosilica.
		GS	10s	7-8 lb/100 ft^2	MWCNT concentration of 0.001 ppb reduced the GS from 8 to 7 lb/100 ft^2. A smaller amount of nanoparticles provided a better effect on the GS.
			10m	7 lb/100 ft^2	Value of GS maintained at 7 lb/100 ft^2 regardless of the concentration of MWCNT added.
	Silica	PV		21-23 cp	No significant impact on PV due to small concentrations (0.001 – 0.2 ppb) of nanosilica.

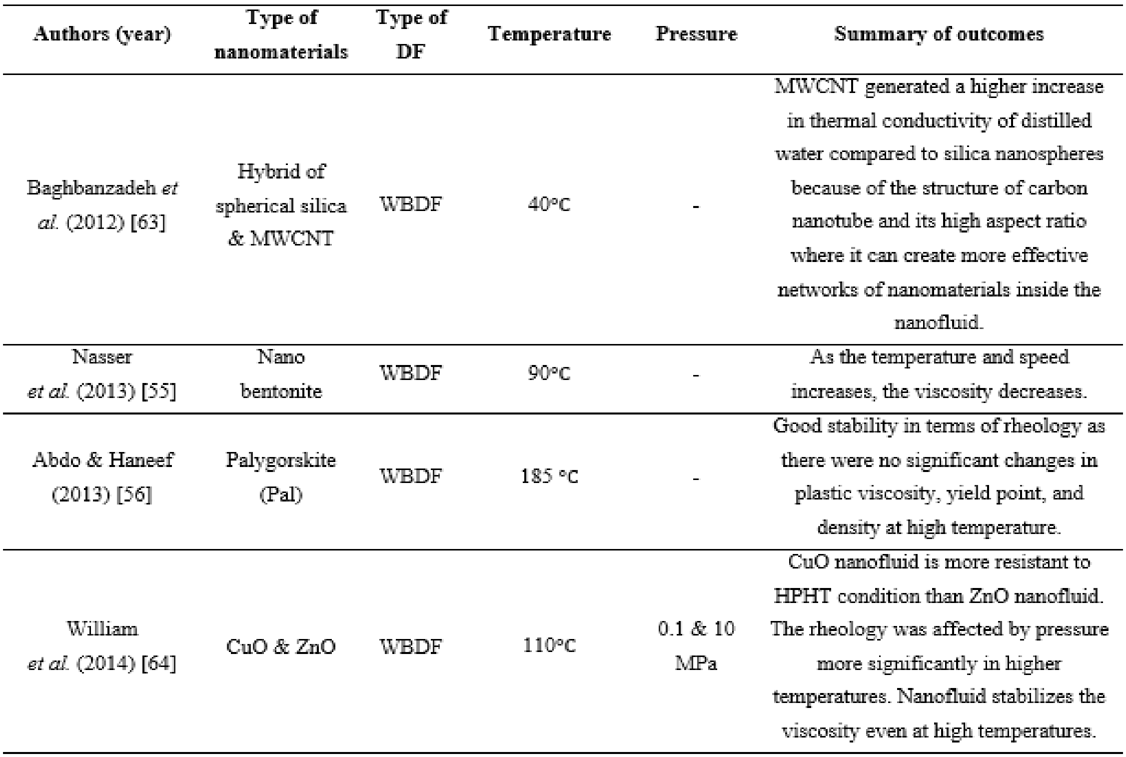


		YP		34-40 lb/100 ft^2	YP increases after adding 0.01 ppb of nanosilica.
		GS	10s	7 lb/100 ft^2	Nanosilica concentration of 0.001-1 ppb reduced the GS from 8 to 7 lb/100 ft^2. A smaller amount of nanoparticles provided a better effect on the GS. Value of GS maintained at 6 lb/100 ft^2 regardless of the concentration of nanosilica added.
			10m	6 lb/100 ft^2	
Smith et al. (2018) [61]	Aluminium oxide	PV		30-38cp	Aluminium oxide and silica nanoparticles up to concentrations of 0.2 and 0.5 wt% showed reduced rheological properties when compared to basic mud. Rheological properties increase slightly at higher concentrations. A large increase in the filtration volume was observed when both aluminium oxide and nanosilica concentration of 0.5 wt% was added. This increase was due to the poor dispersion of nanoparticles in water-based mud.
		YP		30-41 lb/100 ft^2	
		GS	10s	8-10 lb/100 ft^2	
			10m	38-57 lb/100 ft^2	
	Silica	PV		33-40cp	
		YP		38-45 lb/100 ft^2	
		GS	10s	10-13 lb/100 ft^2	
			10m	30-35 lb/100 ft^2	



Katende et al. (2019) [62]	Nanosilica	PV		22-33 cp	Nanosilica alters the rheological properties of 9 and 12 ppg OBM to where it reduces PV, increases YP and GS to the desired range for field application.
		YP		5-24 lb/100 ft^2	
		GS	10s	6-14 lb/100 ft^2	
			10m	12-23 lb/100 ft^2	

Table 5 Nanomaterials effect on the thermal stability of drilling fluids



Authors (year)	Type of nanomaterials	Type of DF	Temperature	Pressure	Summary of outcomes
Baghbanzadeh *et al.* (2012) [63]	Hybrid of spherical silica & MWCNT	WBDF	40°C	-	MWCNT generated a higher increase in thermal conductivity of distilled water compared to silica nanospheres because of the structure of carbon nanotube and its high aspect ratio where it can create more effective networks of nanomaterials inside the nanofluid.
Nasser *et al.* (2013) [55]	Nano bentonite	WBDF	90°C	-	As the temperature and speed increases, the viscosity decreases.
Abdo & Haneef (2013) [56]	Palygorskite (Pal)	WBDF	185 °C	-	Good stability in terms of rheology as there were no significant changes in plastic viscosity, yield point, and density at high temperature.
William *et al.* (2014) [64]	CuO & ZnO	WBDF	110°C	0.1 & 10 MPa	CuO nanofluid is more resistant to HPHT condition than ZnO nanofluid. The rheology was affected by pressure more significantly in higher temperatures. Nanofluid stabilizes the viscosity even at high temperatures.

Yang *et al.* (2015) [65]	SiO_2	NPBM	150-180°C	5.17 MPa	Viscosity decreased as the temperature increased. Mud with lower salinity showed better thermal stability.
Mao *et al.* (2015) [59]	Polymer based nanosilica composite with core-shell (SDFL)	WBDF	220°C	-	Showed increase of yield point to plastic viscosity ratio. High HTHP filtration and high-temperature rheological property showed that SDFL had excellent thermal stability.
Noah *et al.* (2016) [66]	ZnO & $CaCO_3$	PSBR	300°F	500 psi / 3.45 MPa	The viscosity of the mud increased as the nanocomposites increased. The prepared nanocomposites showed increased apparent viscosity, plastic viscosity, and yield point, decrease in fluid loss and increase in electrical stability at HPHT wells.
Smith et al. (2018) [61]	Aluminium oxide & silica	WBDF	120°C	500 psi	Low concentrations of aluminium oxide nanoparticles enhanced thermal stability of WBDF and provided lower degradations compared to mud with nanosilica and base mud. Mud with aluminium oxide nanoparticles also demonstrated a lower increase in shear stress at HPHT.
Katende et al. (2019) [62]	Silica	OBDF & WBDF	66-149°C	600 psi	The optimum concentration of nanosilica in OBDF for improved rheological properties is 0.5 ppb however, the presence of nanosilica slightly increase HPHT filtration loss.

-

Flow rate

The annular flow rate in a concentric annulus is interrelated with parameters such as mud rheology and pump rate. In eccentric annuli, the velocity profile changes depending on rotational speed, and eccentricity. One of the most effective factors in reducing or preventing cuttings bed development is the drilling fluid flow rate [67]. The annular fluid velocity plays a key role in significantly reducing bed developments and most importantly improves cuttings transport in the wellbore. The most effective case is when a turbulent flow regime is present in the annulus. This is to prevent stationary beds from forming in highly deviated wellbores or ensuring cuttings concentration in near vertical wellbores to be less than 5% [68]. According to Gul et al. (2017) [29], wavy annular flow regime which is a flow pattern usually achieved with high gas and liquid flow rates, was the most effective flow regime for cuttings transport.

Based on previous research, cuttings are removed effectively when there is sufficiently high annular velocity [40]. In the same study, they found that cuttings transport performance was reduced as the flow regime shifts from turbulent to transient or laminar flow [40]. Chen et al. (2007) [26] found similar findings where they concluded that higher annular flow velocity decreases the cuttings concentration in the annulus, both in terms of suspended cuttings and cuttings bed. Peden et al. (1990) [11] also concluded that turbulent flow regime predominates in a concentric annulus with suspension and rolling of cuttings at low minimum transport velocity when low viscosity drilling fluids are used. On the other hand, Okrajni & Azar (1986) [14] suggested that different flow regimes are beneficial at different hole inclination angles. Their findings stated that laminar flow has a significant effect on cuttings transport at inclination angles of 0-45° while turbulent flow is significant at 55-90°. Similar effects were observed for turbulent and laminar flow at 45-55°. Meanwhile, Duan et al. (2006) [25] compared the respective performance of water and polyanionic solutions and found that polyanionic solutions performed better, especially when the flow rate increased from 200 to 400 gpm as shown in Figure 5. Yeu et al. (2018) [34], they reported an increment of cuttings transport to 8.6%, 9.8%, and 15.9% for flow rates of 0.4, 0.6, and 1.0 L/s respectively when low-density polyethylene beads were added into water-based mud.

The particle slip velocity is a crucial factor in vertical wellbores, and it is defined as the velocity at which a particle tends to settle in a fluid [10]. Researchers found that the acceptable annular velocity for cuttings transport for typical drilling mud is in the range of 1 to 4 ft/s [69,12]. However, Naganawa et al. (2002) [21] suggested a higher annular velocity where the equivalent critical flow rate was about 6.56 ft/s for highly inclined annulus when using non-Newtonian conventional PHPA fluid. According to Heshamudin et al. (2019) [33], adding polypropylene beads in water-based mud while the mud is in a turbulent flow with a Reynolds number of 6620 caused the inelastic collision of beads and cuttings to increase in the well and ultimately increased the final velocity of cuttings which was proven beneficial for cuttings transport.

Changes in liquid flow rate affect cuttings transport more than gas volume flow rate (Li et al., 2001). At a given flow rate, bed thickness increases with an increase in foam quality [23]. When liquid flow rates are high (>150 gpm), the injection of gas has a positive impact on cuttings transportation. However, when the liquid flow rate is <150 gpm, increasing gas-liquid ratio decreases hole cleaning efficiency [24]. In short, a higher flow rate is often beneficial for cuttings transportation especially in preventing cuttings bed formation at critical angles. However, limitations in the available pump pressure at the rig site make it hard to always achieve a turbulent flow. In such instances, the rheological properties of the mud would have to be adjusted to reduce the viscosity to achieve the required flow rate and for rapid drilling. Some of the key findings are tabulated in Table 6.

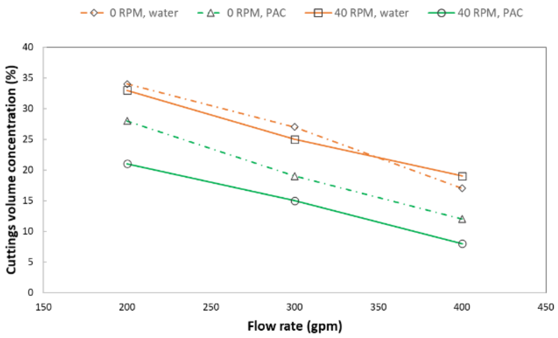
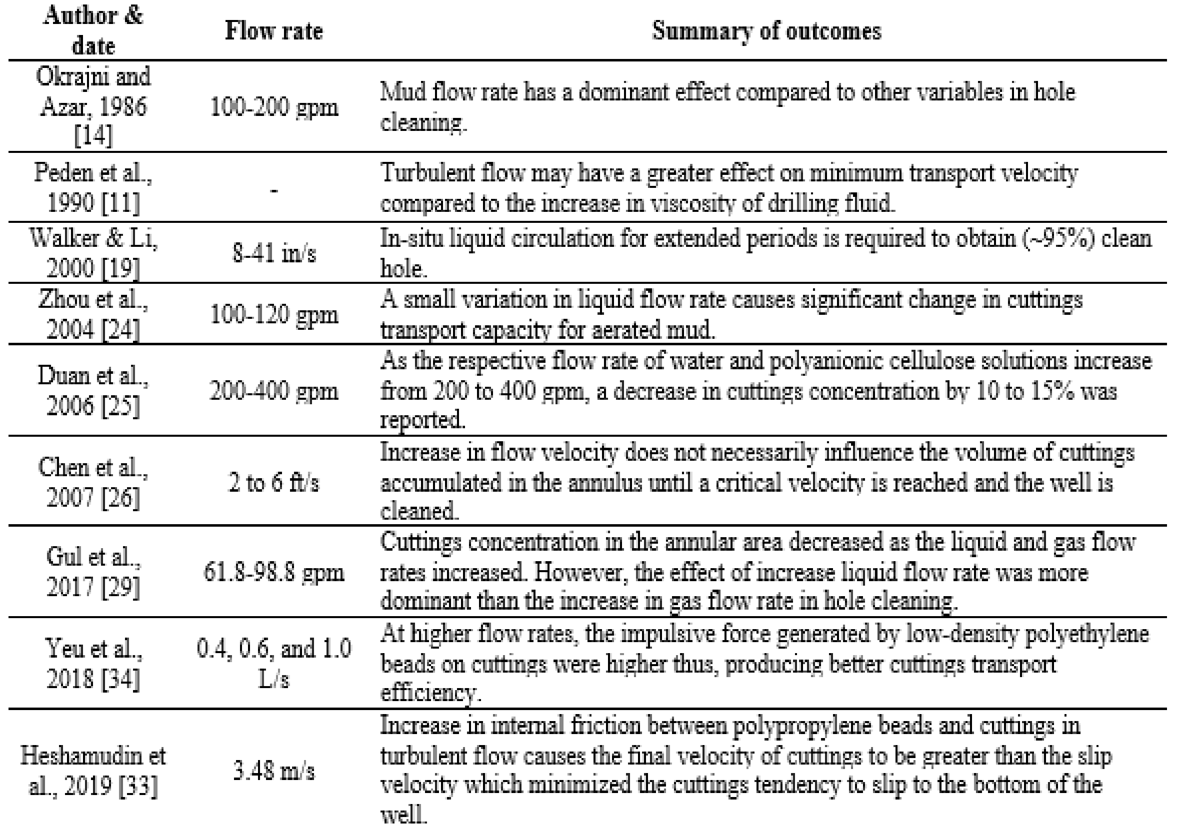


Figure 5 Different drilling fluids comparison at 70° inclination for 0.45 mm cuttings (adopted from Duan et al., 2006 [25])

Hole inclination

Rise in well deviation from vertical shows a significant negative influence on hole cleaning as reported in several studies [14, 16, 70]. Tomren (1979) [71] conducted an experimental study on cuttings transport in inclined wellbores and included a radial component to the terminal settling velocity. He categorized the inclinations into three major sections: 0°-30°, 30°-50° and 50°-90°. His findings mentioned that as the deviation angle increases from vertical to horizontal, the hydraulic power constraint will also need to increase for adequate wellbore cleaning. According to Sifferman and Becker (1992) [16], at deviated sections, cuttings settle in a vertical direction, but the fluid velocity has a reduced vertical component. This causes a decrease in cuttings suspension and results in faster cuttings settling

Table 6 Main findings of the effect of flow rate on the hole cleaning process



Author & date	Flow rate	Summary of outcomes
Okrajni and Azar, 1986 [14]	100-200 gpm	Mud flow rate has a dominant effect compared to other variables in hole cleaning.
Peden et al., 1990 [11]	-	Turbulent flow may have a greater effect on minimum transport velocity compared to the increase in viscosity of drilling fluid.
Walker & Li, 2000 [19]	8-41 in/s	In-situ liquid circulation for extended periods is required to obtain (~95%) clean hole.
Zhou et al., 2004 [24]	100-120 gpm	A small variation in liquid flow rate causes significant change in cuttings transport capacity for aerated mud.
Duan et al., 2006 [25]	200-400 gpm	As the respective flow rate of water and polyanionic cellulose solutions increase from 200 to 400 gpm, a decrease in cuttings concentration by 10 to 15% was reported.
Chen et al., 2007 [26]	2 to 6 ft/s	Increase in flow velocity does not necessarily influence the volume of cuttings accumulated in the annulus until a critical velocity is reached and the well is cleaned.
Gul et al., 2017 [29]	61.8-98.8 gpm	Cuttings concentration in the annular area decreased as the liquid and gas flow rates increased. However, the effect of increase liquid flow rate was more dominant than the increase in gas flow rate in hole cleaning.
Yeu et al., 2018 [34]	0.4, 0.6, and 1.0 L/s	At higher flow rates, the impulsive force generated by low-density polyethylene beads on cuttings were higher thus, producing better cuttings transport efficiency.
Heshamudin et al., 2019 [33]	3.48 m/s	Increase in internal friction between polypropylene beads and cuttings in turbulent flow causes the final velocity of cuttings to be greater than the slip velocity which minimized the cuttings tendency to slip to the bottom of the well.

velocities at greater hole inclinations. Figure 6 shows the cuttings behaviour in inclined and horizontal annuli.

At lower hole angles from vertical, mud velocity has the most significant effect compared to mud weights and rotary speeds on cuttings bed size [16]. Azar (2006) [72] found that at 25° to approximately 45°, a sudden pump shutdown can cause cuttings sloughing to the bottom of the wellbore and it may result in mechanical pipe sticking. Saasen (1998) [44] concluded that vertical holes or at low inclination angles from vertical, requires a shear-thinning fluid with sufficient viscosity for effective hole cleaning.

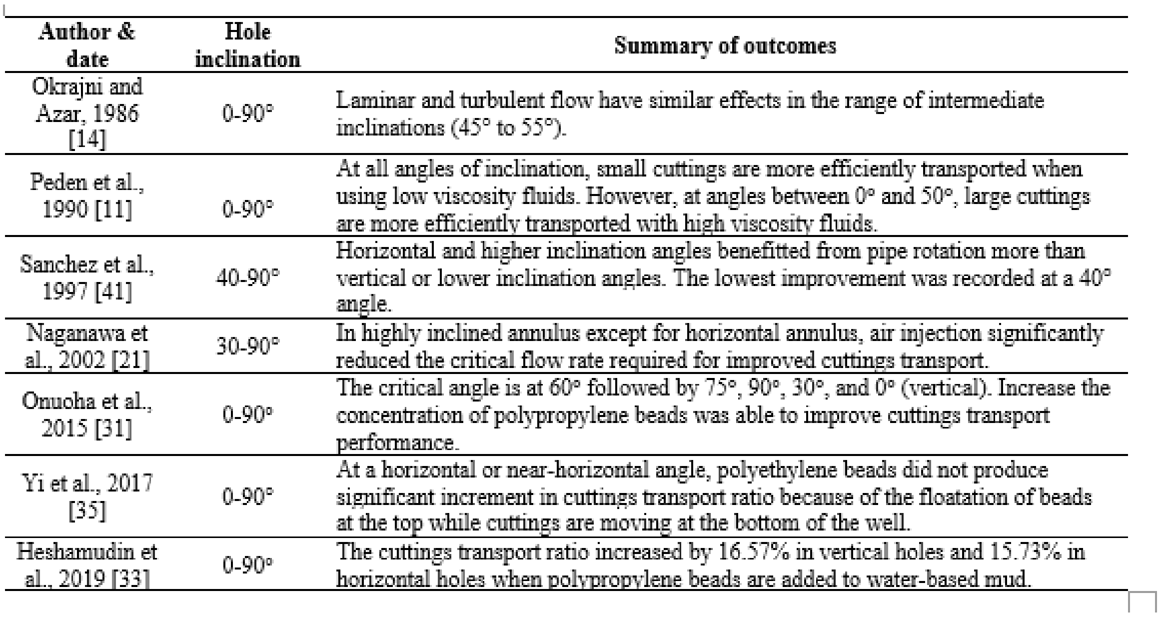
Hole angles between 40-60° are the worse for cuttings rolling and suspension transport mechanism [11]. Hole inclination of 40-45° experiences the poorest cuttings transport when low flow rates are used [14]. Meanwhile, mathematical model and experimental results by Brown et al. (1989) [15] concluded that the poorest cuttings removal rates occur at angles 50-60°. Studies conducted on horizontal wells identified four different flow regimes: bubble, elongated bubble, slug and wavy annular [29]. At this angle, low flow rates and high rotary speeds produced the best results [41]. These findings contradict the findings by Naganawa et al. (2002) [21] as they mentioned that a high annular velocity of about 1.5 m/s was required to transport cuttings effectively at the same angle. This proves that high pipe rotational speed is imperative when annular velocity is inadequate due to insufficient pump rates at horizontal sections. Li et al. (2014) [73] concluded that flow rates of less than 0.6 m^3/min in horizontal or near horizontal wellbores (60-90°) results in stationary cuttings bed in the annulus.

Previous studies have yielded diverse outcomes when testing different types of fluids. Specifically, when utilizing foam, there appears to be minimal impact on bed thickness at inclination angles ranging from 70 to 90 degrees [23]. Under horizontal conditions, water testing demonstrated increased difficulty in transporting smaller cuttings, while no significant influence on cuttings concentration was observed between hole angles of 70 to 90 degrees from the vertical [25]. The introduction of polypropylene beads into water-based mud was found to enhance cuttings transportation in both vertical and horizontal wells [33].

Additionally, nanosilica-based mud exhibited improved cuttings transportation efficiency across all inclinations, with notable enhancements, particularly at critical angles (30 to 60 degrees) [37]. Furthermore, as the hole inclination increased from these critical angles to a horizontal position (60 to 90 degrees), the cuttings transport performance improved by up to 40% when using mud containing bentonite and carboxymethyl cellulose (CMC) [40].

In both low and high angled wells, a high mud velocity is favourable for adequate hole cleaning. If the mud velocity is low at horizontal or near horizontal sections, drill pipe rotation is required to prevent cuttings bed formation. Drill pipe rotation is even more imperative at critical angles (40-60°). This is further discussed in the next section. Some of the key findings of hole inclination on hole cleaning are tabulated in Table 7.

Table 7 Main findings of the effect of hole inclination on the hole cleaning process



Author & date	Hole inclination	Summary of outcomes
Okrajni and Azar, 1986 [14]	0-90°	Laminar and turbulent flow have similar effects in the range of intermediate inclinations (45° to 55°).
Peden et al., 1990 [11]	0-90°	At all angles of inclination, small cuttings are more efficiently transported when using low viscosity fluids. However, at angles between 0° and 50°, large cuttings are more efficiently transported with high viscosity fluids.
Sanchez et al., 1997 [41]	40-90°	Horizontal and higher inclination angles benefitted from pipe rotation more than vertical or lower inclination angles. The lowest improvement was recorded at a 40° angle.
Naganawa et al., 2002 [21]	30-90°	In highly inclined annulus except for horizontal annulus, air injection significantly reduced the critical flow rate required for improved cuttings transport.
Onuoha et al., 2015 [31]	0-90°	The critical angle is at 60° followed by 75°, 90°, 30°, and 0° (vertical). Increase the concentration of polypropylene beads was able to improve cuttings transport performance.
Yi et al., 2017 [35]	0-90°	At a horizontal or near-horizontal angle, polyethylene beads did not produce significant increment in cuttings transport ratio because of the floatation of beads at the top while cuttings are moving at the bottom of the well.
Heshamudin et al., 2019 [33]	0-90°	The cuttings transport ratio increased by 16.57% in vertical holes and 15.73% in horizontal holes when polypropylene beads are added to water-based mud.

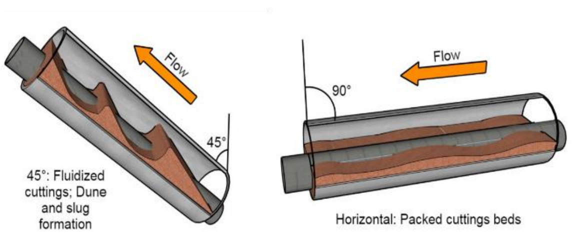


Figure 6 Fluid and cuttings behaviour in inclined and horizontal holes (adopted from Sifferman and Becker, 1992 [16])

Hole eccentricity and drill pipe rotation

The effect of annular eccentricity of the drillpipe resulting from drilling at an inclined angle and weight on bit is significant towards cuttings transportation in the annulus [74]. As the pipe rests on the lower side of the borehole due to gravity at inclined angles, a very narrow gap below the pipe is formed and causes a restriction in fluid flow. This restriction reduces the drilling fluid velocity and reduces the area for cuttings to be transported out of the borehole. In a lot of cases, as the eccentricity increases, cuttings are trapped in this narrow section and start to accumulate which leads to cuttings bed formation. Therefore, according to Tomren et al. (1986) [75], the best cuttings removal occurs when the drill pipe is concentric which is when the drill pipe is at the centre of the hole. However, depending on the well trajectory during the drilling operation, the effect of hole eccentricity may be unavoidable.

Based on Saasen (1998) [44], drillpipe rotation would have similar effects on the hole cleaning performance of both water- and oil-based muds unless the fluids show highly viscoelastic characteristics. The cuttings transportation at the narrow side of an eccentric wellbore can be improved by rotating the drill pipes [11] [76]. Sifferman et al. (1992) [16] concluded that at highly deviated wellbores, small cuttings and low ROP are the most desirable conditions for using pipe rotation effectively. The formation of Taylor vortices (after a specific rotational speed) assists in increasing the lift force in horizontal sections [41,77].

At angles of 55-90° from the vertical, the removal of settled cuttings in the annulus increases with increasing rotary speed [14]. At lower annular velocity (120 ft/hr), the effect of drillpipe rotation is more significant compared to higher annular velocity (240 ft/hr) [16]. With pipe rotation, the lowest hole cleaning improvement was achieved at 40° while the highest was at the horizontal section because, the mechanical agitation is more significant at high angles [41]. Drill pipe rotation combined with polymeric drilling fluids proved to be efficient in transporting small cuttings for horizontal or highly inclined wells [25]. When pipe rotation of 150 rpm was applied, further improvements in cutting transport ratios between 14.9-21.7% and 8.9-23% were observed for 9 and 12 ppg water-based muds with nanosilica respectively as shown in Figure 7. This is because pipe rotation introduces centrifugal force within the annulus which assists the transportation of cuttings out the borehole [37]. Meanwhile, a study done by Heshamudin et al. (2019) [33] mentioned that when pipe rotational speed increased from 0 to 60 rpm, cuttings transport ratio increased between 2.14 to 4.12% depending on the cuttings size. A summary of the key findings is tabulated in Table 8.

As mentioned previously, drillpipe rotation prohibits the development of cuttings bed hence it improves hole cleaning. Drillpipe rotation during drilling creates a turbulent flow [51]. As the drillpipe stops rotating, the cuttings bed starts to develop. A high rotary speed with a high viscosity mud would be the best option to transport small-sized cuttings. In the absence of drillpipe rotation, a low viscosity mud cleans the wellbore better than a high viscosity one. With that said, there is a threshold point for drillpipe rotation speed after which the efficiency of drilled cuttings lifting becomes constant [52].

Table 8 Main findings of the effect of pipe rotation on the hole cleaning process

Author & date	Pipe rotation	Summary of outcomes
Okrajni and Azar, 1986 [14]	50 rpm	Pipe rotation does not only introduce mud axial flow, but also tangential flow which produces minor turbulence. This results in a mechanical action acting on the bed.
Peden et al., 1990 [11]	0-120 rpm	Pipe rotation has no significant effect on hole cleaning in large annuli whilst major improvements can be obtained for small annular clearances.
Sifferman and Becker, 1992 [16]	0-60 rpm	Drillpipe rotation induces tangential component of mud velocity and the effect is more significant at lower annular mud velocities.
Sanchez et al., 1997 [41]	0-175 rpm	Drillpipe rotation majorly affects hole cleaning even after drilling has stopped; this reduces the residual cuttings concentration in the annulus.
Saasen, 1998 [44]	-	Viscoelastic fluids would perform well with drillpipe rotation and vice versa.
Duan et al., 2006 [25]	0-80 rpm	The improvement of cuttings transportation by pipe rotation was twice as large for smaller cuttings (0.45 mm) compared to larger cuttings (1.4 mm).
Osgouei, 2010 [50]	0-120 rpm	Increase pipe rotation decreases cuttings concentration in the annulus and as a result, decreases the frictional pressure losses.
Heshamudin et al., 2019 [33]	0-150 rpm	The optimum pipe rotation speed was 60 rpm.

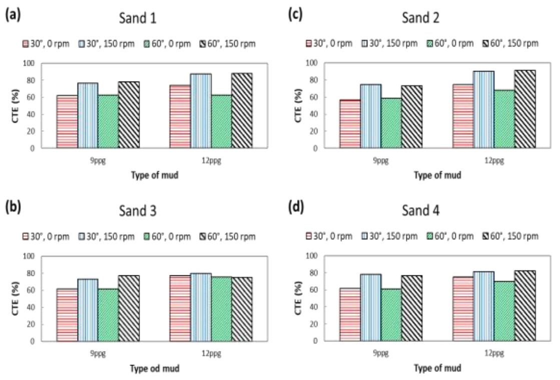


Figure 7 Cuttings transportation improvement of mud with 1.0 ppb nanosilica; without and with 150rpm pipe rotation for different cuttings sizes: (a) 1.40-1.69 mm, (b) 1.70-1.99 mm, (c) 2.00-2.19 mm, and (d) 2.80-4.00 mm at critical angles 30° and 60° (adopted from Boyou et al., 2019 [37])

Cuttings sizes

A summary of key findings is tabulated in Table 9.

Table 9 Main findings of the effect of cuttings size on the hole cleaning process

Author & date	Cuttings size (mm)	Summary of outcomes
Peden et al., 1990 [11]	- 1.70-3.35	Small cuttings are the easiest to remove except at low angles when larger cuttings are efficiently transported by high viscosity fluids
Sifferman & Becker, 1992 [16]	-2.00-4.75	Drillpipe rotation had the greatest effect on small cuttings (2 mm) at near-horizontal inclinations with low ROP (50 ft/hr).
Sanchez et al., 1997 [41]	- 2.54-6.35	Small cuttings are harder to transport unless a high viscosity mud is used coupled with a high drillpipe rotation.
Walker & Li, 2000 [19]	- 0.15-7.00	Spherical particles with an average size of 0.76 mm are the hardest to clean out while smaller particles are the easiest for solids transport.
Duan et al., 2006 [25]	- 0.45-3.30	Larger cuttings are easier to be transported in all flow rates but when polymeric fluid is used with the presence of drill pipe rotation, smaller cuttings are transported farther and avoid forming a cuttings bed.
Hakim et al., 2018 [36]	- 0.50-4.00	The use of polypropylene beads in water-based mud improved cuttings transport efficiency by more than 10% for all cuttings sizes tested compared to basic mud.
Boyou et al., 2018 [32]	- 0.50-3.34	Smaller cuttings were easier to transport compared to larger cuttings.
Heshamudin et al., 2019 [33]	- 0.50-2.00	Larger cuttings are more difficult to remove because of its higher slip velocity which increases the tendency for a cuttings bed to form.

Cuttings that are drilled from limestone or clay stone are usually larger. Meanwhile, sandstones that are suspended in the mud are usually smaller in size and rounder in shape [51]. According to Pedrosa et al., (2021) [78], higher amounts of smaller particles are found in highly deviated wellbores, between 70-90°, whereas higher amounts of larger particles are found in wellbores between 0-60°. Previous research works found that larger cuttings are easier to remove when they are in suspension during the occurrence of bed development especially in deviated wellbores [12, 25,70,79]. Walker & Li (2000) [19] found that spherical particles with an average size of 0.76 mm were difficult to transport. This is because when smaller cuttings start to accumulate in the annulus at highly deviated angles, the open spaces between two cuttings are smaller compared to larger cuttings; making the cuttings bed more compact and harder to erode unless higher flow rates are applied. This is consistent with the outcomes of the studies conducted by Gavignet and Sobey (1989) [80] and Ahmed (2001) [81].

The cuttings build-up process in the annulus is highly dependent on the critical flow velocity which is the minimum transport velocity needed to overcome bonding, contact, and gravitational forces of cuttings [13, 68, 82,83,84]. Maintaining the critical flow velocity to ensure a continuous upward movement of cuttings in the annulus during drilling operations is incredibly difficult. Thus, it is important to accurately calculate the cuttings settling velocity [85]. Ford et al. (1990) [86] observed that as the cuttings size decreases, the minimum transport velocity required for cuttings rolling and cuttings suspension decreases. This means that in terms of minimum transport velocity, smaller cuttings are easier to transport. This was supported by Peden et al. (1990) [11] and Martin (1996) [17] as they concluded that smaller cuttings are easier to transport at all inclination angles in the annulus when pipe rotation is not present. In vertical wells, smaller cuttings are easier to transport with less force. Most researchers concluded this observation by measuring the total annular cuttings concentration in the annulus.

Other findings found that polymer beads could improve cuttings transportation of diverse sizes in the wellbore. A study found that as the concentration of polyethylene (PE) and polypropylene (PP) polymer beads increased, the cuttings removal increased where the smallest cuttings size (0.50-0.99 mm) showed the highest cuttings removal percentage [36]. Heshamudin et al. (2019) [33] also supported that smaller cuttings are easier to transport at various hole angles regardless of the concentration of polypropylene beads added as well as with and without pipe rotations.

Boyou et al. (2019) [37] stated that smaller cuttings (1.40-1.69mm) were more efficiently removed in vertical wellbores when drilling fluids with nanosilica concentrations of 1.0 and 1.5 ppb were used. Meanwhile, when using the same concentrations of nanosilica, larger cuttings (2.80-4.00mm) were easier to remove in horizontal wellbores. Even with the presence of nanoparticles in the mud system, the same conclusions are drawn; larger cuttings are harder to transport in vertical to near vertical wellbores and smaller cuttings are harder to transport in horizontal or near horizontal wellbores. However, with the optimum concentration of nanoparticles, cuttings transport efficiency is enhanced when compared to mud without nanoparticles. On the other hand, Sifferman & Becker (1992) [16] concluded that large cuttings beds of more than 20% of the annular area and made from small cuttings are effectively removed with pipe rotation. Thus, the presence of nanosilica, high flow rate, and pipe rotation could prevent the accumulation of cuttings or decrease the cuttings bed area in the annulus.

Modelling the hole cleaning process

Hole cleaning analytical and numerical modelling approaches provide tools to simulate the performance of the process in the wellbore during drilling operations at different conditions. In this section, several analytical and numerical modelling approaches for the hole cleaning process are discussed.

One of the earliest analytical modelling studies was conducted by Larsen et al. (1997) [12]. They developed a new design model that could predict the required key parameters for successful hole cleaning such as the critical transport fluid velocity, average cuttings travel velocity, and annular cuttings concentration in high-angle holes from 55° to 90° from the vertical. They concluded that low viscosity muds perform better in high-angle wells because in an eccentric annulus; drill pipe resting on tool joints on the lower side of the hole causes a flow divergence from the narrow section to the open section of the pipe more than that when higher viscosity muds are used. On the other hand, Malekzadeh & Mohammadsalehi (2011) [87] conducted a hole cleaning study using numerical tools where they predicted the critical transport velocity and calculated the optimum flow rate required for transporting cuttings at all inclination angles from 0° to 90°. The YS5 horizontal well in Yort-e-Sha field in Iran is used to demonstrate the application of this method. Their findings showed that a continuous increase in flow rate was required for hole cleaning at hole inclinations from 0° to 55°. They also found that at vertical sections; increasing yield point had a greater effect on hole cleaning than solely increasing plastic viscosity, or in other words, the ratio of YP/PV should be high for effective hole cleaning. Meanwhile, this is not the case for highly inclined wellbores (e.g. at 70°) where increasing YP and PV increases the minimum velocity required for hole cleaning as shown in Figure 8. A similar numerical study was also conducted by Kamyab & Rasouli (2016) [88] where the key aspects investigated were determining the minimum cuttings transport velocity, hole inclination angles, Boycott movement of cuttings, cuttings density, and cuttings concentration on hole cleaning. They investigated three different drilling fluids' performances on hole cleaning namely, water, then water and polymer (Corewell), as well as water, polymer (Corewell) and xanthan gum (Xan-Bore). They simulated the mud with polymer flowing at a velocity of 1.3 m/s with cuttings sizes ranging from 2.36 to 4.7 mm at 45° hole angle. Their findings showed that a stationary bed is formed at the lower side of the annulus, therefore a higher flow velocity was required to transport stationary cuttings to the moving bed.

Other modelling studies include Ozbayoglu et al. (2003) [23] and Rooki et al. (2014) [89] where they investigated cuttings transport phenomena with the effect of foam quality. Rooki et al. (2014) [89] studied the effect of drill pipe rotation, foam velocity, and hole inclination in both concentric and eccentric annuli. They stated that for eccentric cases, pipe rotation generates rotational flow near the bottom of the wellbore. This pipe rotation results in a smaller area with low axial velocity in the x-direction. This causes a decrease in the accumulation of particles at the bottom of the wellbore. This effect is not significant for concentric annulus, especially when high fluid velocity is present. Ozbayoglu et al. (2003) [23] presented a model consisting of three layers which are the motionless bed, moving foam-cuttings mixture, and cuttings-free foam. The computer simulator was able to solve the equations for flow velocity, slip velocity, cutting bed height, the concentration of flowing cuttings and pressure drop simultaneously to a reasonable degree. However, they reported that the model has some limitations as it only applies to the three-layer case with a stationary bed. Furthermore, the model is only suitable to be used for hole angles greater than the critical sliding angle.

Other than that, Zakerian et al. (2017) [90] investigated the effects of drilling fluid rheology and cuttings density on pressure drop, deposit ratio, and string stress on cuttings transport in horizontal wells. The simulated results are compared with experimental database for systematic validation. As the drilling fluid density/operational density doubled, the cuttings precipitation ratio reduced by 32.9% and the stress applied on the drill string and the pressure drop increased by 4.59 and 5.97%, respectively. Meanwhile, as the drill cuttings density/operational density doubled, cuttings precipitation ratio increased by 200%. Also, Guo & Li (2017) [91] analyzed the change in fluid rheology, velocity, and pressure of the liquid in the annulus; however, they included another key aspect in their study which was with and without pipe rotation. They compared their numerical model with Wang's model and found that their model overestimates the cuttings bed height when the flow rate is low and underestimates it when the flow rate is high. They concluded that drillpipe rotation increases cuttings velocity which reduces cuttings concentration in the annulus and that a sharp decline of cuttings bed results when pipe rotation is between 80 to 120 rpm.

The transient behaviors of cuttings transport, slip velocity and concentration of suspended cuttings, cuttings bed height, annular pressure, and equivalent circulating density of a complex extended reach well were predicted by the two-layer-model transient-cuttings-transport simulator developed by Naganawa et al., 2017 [92]. The model was validated as the model parameters were determined from the experimental results of a large-scale flow loop. When field data is used together with the transient model, the authors found that it has the potential to underpin the transient-cuttings-transport behavior and downhole conditions in directional wells. However, adjustments on friction factors and drill pipe rotation consideration are still required. Later, Epelle & Gerogiorgis (2018) [93] conducted a slightly more extensive study which included the effects of particle sphericity: 0.5, 0.75, and 1 with diameters of 0.002, 0.003, 0.004, 0.005 and 0.008 m on the flow dynamics around bends (horizontal to inclined and inclined to vertical sections) as shown in Figure 9. They concluded that increased dispersion and faster travel in the annulus are experienced by non-spherical particles compared to perfectly sphere particles. The annular eccentricity, gravitational resistance and reduced particle lifting by drill pipe rotation are the reasons for high deposition of particles in the inclined-to-vertical (upper) bend.

Apart from that, there were also other modelling studies which investigated unique problems or provided new insights on drilling challenges involving hole cleaning. For example, Salehi et al. (2013) [94] presented analytical and numerical models to clarify and optimize parameters for casing drilling applications by providing new insights on the "Smear Effect". They considered various pipes to open hole ratios, mud cake contacts, and geomechanically properties of both mud cake and formation for enhancing wellbore integrity and hole cleaning. According to their analytical model, an increase in the ratio of casing size to annulus size results in a reduction in casing displacement during rotation. This decrease in displacement subsequently leads to a decrease in the contact force between the casing and the mud cake. They also concluded that when the casing to hole size ratio exceeded 0.8, hydraulic results showed a sharp increase in the bottom-hole pressure. Furthermore, Minakov et al. (2018) [95] investigated various nanoparticles (Aluminum oxides, Titanium oxides, and silicon) with different sizes and analyzed their effect on drilling fluid's rheological behavior, pressure loss, and cuttings transport for laminar flow regime in vertical holes. The presence of nanoparticles in bentonite-based drilling fluid increases the cuttings transport performance by 17% and decreases the average slip velocity of sludge particles by 1.7 to 2.08 times. However, the pressure losses while pumping the drilling fluid increases by 2.5 times. This is attributed to the increase in the effective viscosity of the mud. In addition to that, Forshaw et al. (2020) [7] modelled cuttings bed accumulation by accurately depicting the size, location of beds in the wellbore and cuttings bed evolvement over time. The probability index of a poor hole cleaning event for each inclination section can be calculated, and the agent gives out an alarm when the probability index exceeds a pre-defined threshold probability. A case study was presented to demonstrate the viability of this real-time engineering modelling, using recorded real-time data of a well in the North Sea. Figure 10 shows the steady-state simulation models in pre-, real-time, and post-well phases of well construction. The case study presented that the real-time model returned to steady-state simulation and showed potential cuttings beds accumulation at 40° inclination section. Table 10 shows a summary of different modelling approaches for the hole cleaning process.

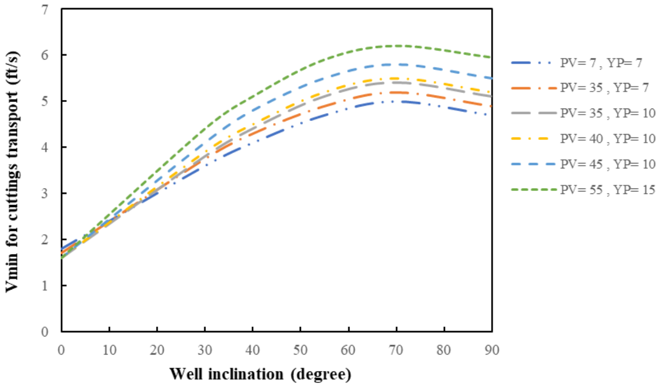


Figure 8 The effect of change in rheological properties on minimum velocity (V_{min}) (adopted from Malekzadeh & Mohammadsalehi, 2011 [87])

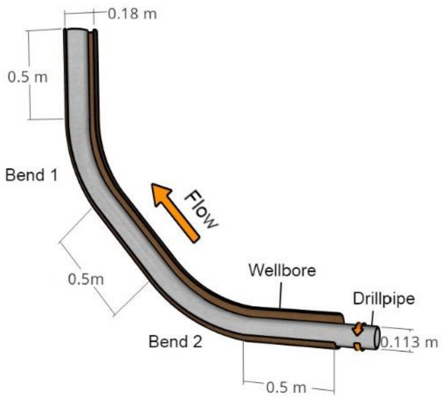


Figure 9 Annular flow geometry (adopted from Epelle & Gerogiorgis, 2018 [93])

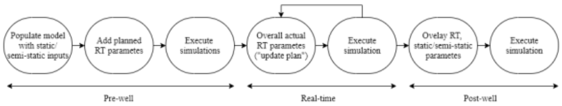


Figure 10 Pre- , real-time, and post-well phases of well construction (adopted from Forshaw et al. 2020 [7])

Table 10 Analytical and numerical studies on the hole cleaning process

Author(s)	Modelling type	Approach	Summary of outcomes
Larsen et al., 1997 [12]	Analytical	Developed an empirical correlation coupled with the results from the hole cleaning experimental study in a 5 in full-scale flow loop. The model predicts the required critical transport fluid velocity, the average cuttings travel velocity and the annular cuttings concentration.	Water or low viscosity muds are more beneficial for high-angle wells because a higher fluid velocity is present below the drill pipe.
Malekzadeh & Mohammadsalehi, 2011 [87]	Analytical	The model predicts and calculates the optimum flow rate required for cuttings removal for all range of inclinations. The hole cleaning optimization program combines Larsen's model (used to find the minimum flow rate for cuttings removal) and Moore's correlation (used to find the slip velocity of cuttings in vertical wells) as well as drilling hydraulic optimization.	The minimum flow rate for cuttings transport at all inclination can be identified. Optimizing the flow rate is possible thus, hydraulic optimization and efficient hole cleaning can be achieved.
Salehi et al., 2013 [94]	Analytical and numerical	The simulation models wellbore area of the various pipe to open hole (casing-diameter to hole-diameter ratio) ratios and mudcake contacts while considering geomechanical properties in both the mudcake and formation. Actual operation data from one of the fields from South Texas was used for simulations. Contact force for each set of casing sizes and rotations were calculated using analytical models and these forces formed the boundary conditions in finite element models to evaluate mud cake failure.	Finite-element models showed that there was no mud cake failure when casing rotation reaches 100 rpm; however, due to uncertainties of mud cake properties such as yield strength, this cannot be confirmed.
Rooki et al., 2014 [89]	Numerical	Investigated the effect of foam quality, foam velocity, drill pipe rotation, and wellbore inclination on cuttings transport in both concentric and eccentric annulus. The liquid-solid flow was simulated using the Euler-multiphase flow approach. Specific appropriate boundary and initial conditions solved the conservation of mass and momentum equations.	Increase in foam quality, foam velocity and drill pipe rotation increased the cuttings transport ratio. Higher foam quality (90%) shows a decrease in cuttings transport ratio from 0.98 to 0.81 when hole angle deviates from 0° to 45° with fixed foam velocity of 5 ft/s in a concentric annulus. The ratio remains mostly constant (only varies slightly) between the hole angle of 45° to 90°.

		The rheological parameters of Herschel Bulkley and Power Law models were estimated using the generic algorithm (GA) method based on earlier work [96]. The Power law model has a lower sum square error (SSE) and was chosen for the computational fluid dynamic simulation.	
Kamyab & Rasouli, 2016 [88]	Numerical	Key aspects investigated were hole inclination angles, determination of minimum transport velocity, Boycott movement of cuttings, cuttings density, and cuttings concentration on hole cleaning. The Eulerian Granular model was used to simulate fluid and solid flow in the annulus. An average value was used to track individual particles flowing in the fluid. This study applied shear-stress transport (SST) turbulent kinetic energy (k) for specific dissipation rate (ω) which is also known as (SST) $k-\omega$ and the Phase Coupled SIMPLE solution method was chosen to solve the equations of momentum.	The performance of drilling fluids with higher viscosity was able to suspend cuttings more efficiently and produced an even distribution in the annulus compared to water.
Zakerian et al., 2018 [90]	Numerical	The model investigated the effect of drilling fluid and drill cuttings density on pressure drop, cuttings precipitation, and stress applied on the drill string. Mix model equations were presented using the continuity equation, momentum equation, and velocity equation for the comprehensive simulation and modelling. All flow regimes are laminar. Central difference method was used to solve diffusion terms of the equations and the first-order upwind scheme was used to estimate the magnitude of displacement terms in the momentum equations and volumetric fraction on the sides of the computational cells.	Increase in cuttings density leads to an increase in cuttings precipitation and pressure drop due to mud flow resistance.
Guo & Li, 2017 [91]	Numerical	Investigated the effect of pipe rotation, eccentricity, flow rate, fluid properties cuttings diameter and concentration on cuttings bed height and velocity. They adopted the Euler multiphase flow model using mathematical models from the continuity equation and momentum equation. They verified their model by comparing it with Wang's model.	The presence of drillpipe rotation turns the axial motion of cuttings to helical motion and the velocity as well as the distribution of cuttings in the annulus becomes symmetrical.
Naganawa et al., 2017 [92]	Analytical and numerical	The model predicts the transient behaviours of cuttings transport, including the concentration and slip velocity of suspended cuttings, cuttings bed height, annular pressure, and equivalent circulating density along the entire trajectory of a complex extended-reach well. An extension of the semi-implicit method for modelling fluid flow to eliminate the restriction of the Courant-Friedrichs-Lewy condition that exists in conventional semi-implicit schemes was adopted. The numerical procedure used was the stability-enhancing two-step (SETS) method.	The SETS method improves computation time which makes it possible for larger timesteps without sacrificing numerical stability.

Epelle & Gerogiorgis, 2018 [93]	Numerical	Aim to improve the limitation of particle shape which affects turbulent modulation and dispersion characteristics as well as particle fluid interactions. The Syamlal-O'Brien drag model was incorporated into the Eulerian-Eulerian model and made it possible to determine the flow peculiarities of non-spherical cuttings which affect the transport phenomena in an annular flow geometry. SIMPLE was adopted as the pressure velocity coupling scheme.	Translational motion of drilled cuttings is experienced in the vertical annular section while swirling motion is observed in other sections of the annulus.
Minakov et al., 2018 [95]	Numerical	Investigate the effect of nanoparticles of different sizes and chemical components on the rheological behaviour of drilling fluids, pressure loss, and cuttings transport on vertical borehole for laminar flow regime. The flow behaviour of cuttings and respective drilling fluids in the annulus was studied using the Eulerian-Eulerian two-phase flow model. The Herschel Bulkley model was used. A second-order upwind QUICK scheme was used to approximate convective terms of the transfer equations. The connection between the velocity and pressure fields was implemented using the SIMPLEC procedure for aligned grids. An iterative method with the use of the algebraic multigrid solver solved the differential equations obtained after discretization of the original system of differential equations.	Nanoparticles significantly change the rheological properties of the drilling fluid and that the effective viscosity begins to manifest at very small weight concentrations.
Forshaw et al., 2020 [7]	Analytical	Simulated transient modelling was used to model a hole cleaning monitoring system that takes signals from algorithmic agents parameters from the surface, downhole, and rheological properties of the drilling fluid. These diagnostic criteria aggregation acts as indicators for identifying the deposition of cuttings beds at different inclination sections of the wellbore.	The simulation allowed specific identification of the area in the wellbore where cuttings bed is accumulating. This framework has significant potential to automate the detection of drilling fluid dysfunctions.

Applications of Artificial Intelligence (AI) and Machine Learning (ML) in Hole Cleaning

Recently, there have been many studies on the applications of machine learning in improving the drilling process, especially with the rising and fast developments of artificial intelligence technologies. The machine learning/data-based models have shown more accuracy than the traditional numerical models. As it is possible now to combine the recorded drilling data and the recorded petrophysical logs in a well and use this combination to improve the drilling process and avoid some of the drilling problems (as; pipe stuck, lost circulations, cutting transport … etc.) [97]. The efficiency of cuttings transport (i.e., hole cleaning) was predicted by two ways either (i) by investigating the concentration of cuttings or (ii) by predicting the cuttings flowing characteristics (such as wall factor or fri ction factor) as summarized in Table 11.

For cutting characteristics, Rooki et al. (2014) [98] stated that the ANN model showed better accuracy compared to mechanistic model and multiple linear regression (MLR). They predict the cuttings concentration during foam drilling using ANN method. The inputs were pumping rate, drilling rate,

wellbore geometry and drilling fluid rheology and density. The average absolute percent relative error (AAPE) values for ANN model, MLR model and mechanistic model were 3.2%, 8.5% and 10.3% respectively. The results show high ability of ANN in prediction compared to tatistical methods. Ozbayoglu et al. (2020) [101] estimated the bed of cuttings height using artificial neural network (ANN) method with an error percentage of less than 10%. The used inputs are cuttings concentration, drilling fluid viscosity and density, pump rates, wellbore geometry and drilling rate. They also developed a traditional model for comparison with the ANN model. They found that the traditional model doesn't fit to different flow regimes, for example, laminar flow requires a different correlation from the one used for turbulent flow. On the contrary, the ANN model can provide good results for different flow regimes.

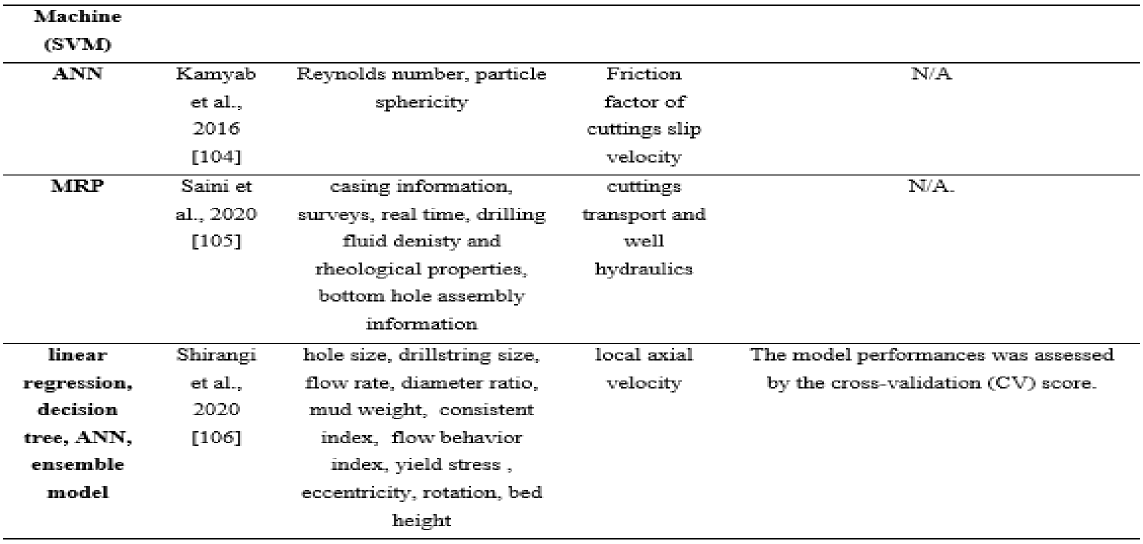
Also, for particles flow characteristics, Kamyab et al. (2016) [104] estimated cuttings slip velocity using ANN method. In this study, the used inputs are the particle's sphericity and Reynolds number. The ANN model covers a wider range (from 0.125 to 1.0) of the particles' sphericity compared to traditional models.

Li et al. (2014) [73] developed a model that can estimate particle settling's wall factor through a cylindrical tube. Their model manages to handle different particle shapes (rectangular prism spherical, and cylindrical). Also, Rooki et al. (2012) [103] used an ANN model to predict the settling velocity of cuttings falling through liquids (Newtonian and non-Newtonian) by using the density and diameter of the spherical particle in addition to the density and rheological parameters of the surrounding liquid.

Moreover, Saini et al. (2020) [105] developed a self-learning cuttings transport model using a Markov rewards process (MRP) model. The inputs are operation parameters (i.e., flow rate) drilling fluid density and rheological properties, and wellbore information (i.e., bottom hole assembly information). This model reduced the non-productive time (NPT) by controlling the cuttings transport performance of the well. Shirangi et al. (2020) [106] predicted the axial velocity using computational fluid dynamics (CFD) data and machine learning algorithms. They used the same inputs as Saini et al. [105], which included the wellbore information, operational parameters, and fluid properties. The performance of the developed model was better than other approaches.

Table 11 Summary of the AI and ML applications in the hole cleaning process

Method	*Authors*	*Inputs*	*Output*	*Results*
Back propagation neural network (BPNN)	Rooki et al., 2014 [98]	Subsurface condition (pressure and temperature), pipe rotation, eccentricity of annulus, foam quality and foam velocity	Cuttings concentration	The prediction has accuracy of AAPE, 5.93% R2,0.914.
Radial basis function network (RBFN)	Rooki and Rakhshkhorshid, 2017 [99]	foam velocity, foam quality, eccentricity of annulus, subsurface condition (pressure and temperature), and pipe rotation.	Cuttings concentration	The prediction has accuracy of AAPE, 5.7% and R2, 0.922.
Support vector machine (SVM)	Al-Azani et al., 2019 [100]	Mud density, mud rheological properties, drilling parameters (e.g. the hole inclination angle, pipe eccentricity), the rate of penetration (ROP), flow rate (GPM), drill pipe rotary speed (RPM) and temperature.	Cutting concentration	The average absolute errors (AAE), 2.6716 % and correlation coefcients (R), 0.9344.
ANN	Ozbayoglu et al., 2020 [101]	Reynolds number, Froude number,	cuttings concentration at the bit Height of cuttings bed	AAPE<10%
ANN	Agwu et al., 2019 [102]	Mud density, mud viscosity, cuttings diameter, cuttings density, and cuttings sphericity	Cutting settling velocity	The ANN had accurate predictions with R2 of 0.978, RMSE of 0.0274.
BPNN	Rooki et al., 2012 [103]	the spherical particles (density and diameter) and of the surrounding liquid (density and rheological parameters) and acceleration of gravity	terminal velocity of solid spheres	The coefficient of determination, R^2, and RMS error in the terminal velocity for all data points were 0.986 and 0.038 m/s respectively.
ANN, Support Vector	Li et al., 2014 [73]	density, fluid density, fluid consistency index, fluid flow behavior index, particle diameter, etc.	Wall factor of particle settling	R = 0.7804.



Machine (SVM)				
ANN	Kamyab et al., 2016 [104]	Reynolds number, particle sphericity	Friction factor of cuttings slip velocity	N/A
MRP	Saini et al., 2020 [105]	casing information, surveys, real time, drilling fluid denisty and rheological properties, bottom hole assembly information	cuttings transport and well hydraulics	N/A.
linear regression, decision tree, ANN, ensemble model	Shirangi et al., 2020 [106]	hole size, drillstring size, flow rate, diameter ratio, mud weight, consistent index, flow behavior index, yield stress , eccentricity, rotation, bed height	local axial velocity	The model performances was assessed by the cross-validation (CV) score.

Recommendations for future research

Although we have summarized many past studies in the hole cleaning area, there are many unknowns in this area that require further research to improve the hole cleaning efficiency for complex structural wells.

Improving experimental flow loop designs

The length, size, and annular dimensions must be suitable to replicate a scaled-down or an actual size well. For instance, the length must be long enough to accommodate the entrance and exit length of the test section to successfully allow sufficient flow development. This was not properly addressed in past literature. Flow loop systems that could replicate high-pressure high-temperature wells should also be studied along with the use of suitable temperature, pressure and other sensors with the correct range and accuracy. Test section inclination should also be studied from 0° to 90° from vertical to test the performance of drilling fluid in every well trajectory to simulate actual extended-reach drilling operations. Furthermore, eccentricity should be considered in dynamic tests and not only in simulations as the probability for eccentric annulus to occur is high at the well site. Finally, most of the past research on dynamic hole cleaning experiments only investigates the performance of water, foam and water-based muds as drilling fluids. The literature on other types of drilling fluids tested in experimental flow loop systems is still scarce.

Comparing simulation Data with experimental or field results

Simulation models should reduce the assumptions related to key parameters which affect hole cleaning performance such as the size and shape of cuttings or taking the average value to track individual particles in the flowing mud. Although these simplifications would greatly reduce the complexity of the model and the time to generate results; they might reduce the accuracy of modeling the hole cleaning performance and the cuttings bed accumulation. Simulation models should be compared or verified with experimental results or even better, with field data for better accuracy. These types of methods are the best way to predict hole cleaning outcomes such as, the location and concentration of cuttings accumulation at certain bends with time when given a certain range of variables. This would be a better way to predict cuttings transport performance. The innovative technologies of machine learning (ML) and reinforcement learning (RL) models can be used for automated and real-time modelling.

Developing new drilling fluids

Many studies in the literature support the use of nanomaterials to be beneficial in improving rheological properties. Although these tests are limited to only rheological properties tests in ambient or high-pressure high-temperature conditions; they are static tests which show only preliminary results of the drilling fluid's potential for proper hole cleaning. Actual dynamic tests which are flow loop experimental findings of incorporated nanomaterials in drilling fluids performance are still scarce. Apart from that, the use of more biodegradable additives in drilling fluids is still in its infant stage. More research should be conducted to develop such drilling fluids to reduce the impact of drilling fluid's waste on the environment.

Conclusions

This paper obtained the following conclusions:

1. Investigating the effects of drilling fluid performance using dynamic tests to assess hole cleaning performances.
2. High viscosity muds perform better in transporting cuttings in the annulus, especially at highly inclined wellbores.

However, the flow rate or drilling fluid velocity must be sufficient or more than the minimum transport velocity; in most cases, this condition falls within the higher end of a laminar flow or a turbulent flow regime depending on cuttings size and viscosity as well as the dimension of the annulus. Higher viscosity muds are, however, not so efficient in hole cleaning for eccentric annulus as they prevent rapid flow at the bottom of the drill pipe for flushing accumulated cuttings. Drillpipe rotation has a positive effect on hole cleaning, especially for eccentric annuli. Improved hole cleaning is achieved when drillpipe rotation of 60 to 150 rpm is present.

3. Dynamic test is imperative to properly test the performance of newly developed drilling fluids, i.e. drilling fluids with nanomaterials as well as environmentally friendly drilling fluids with biodegradable additives for greener and safer drilling operations.

4. Flow loop designs could be improved to better simulate actual drilling operations by replicating high pressure, high temperature environment with different eccentricities.

5. Simulated models should reduce the assumptions of hole cleaning parameters as much as possible and/or neglect certain observed or expected conditions. Rate of cuttings accumulation or time-dependent results are also important to properly study hole cleaning performances.

The cutting-edge technologies of machine learning (ML) and Artificial Intelligence (AI) models can be used for automated and real-time modeling of hole cleaning processes.

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Conflicts of interest

The authors declare no conflicts concerning competing for financial interest.

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