Drilling Parameter Effects on Cuttings Transport in Horizontal Wellbores: A Review

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Abstract Extensive studies on cuttings transport have been conducted by many researchers over the years. In an attempt to better understand the factors influencing cuttings removal in the wellbore, the behaviour of drill-cuttings in the annulus has been simulated and measured under various conditions in the laboratory using mainly water-based and oil-based muds. Furthermore, empirical and semi-empirical correlations as wells as mathematical models have also been developed under specific conditions by other investigators to ease the difficulties and complexities encountered by field engineers during drilling operations. In addition, qualitative hydraulic programmes have also been outlined to provide field guidelines for improved hole cleaning. In recent times, the use of computational fluid dynamics (CFD) in parametric study of cuttings transport has gained popularity due to its ability to handle unlimited number of physical and operational conditions as well as eliminating the need for expensive experimental set-ups. This paper seeks to review the factors or combination of factors affecting cuttings transport as well as the various hydraulic programmes applicable to solving the prevailing field drilling problems in horizontal wellbores.

Keywords Cuttings transport · Drill-cuttings · Hydraulic programmes

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1 Introduction

There are huge amount of literature available on the study of cuttings transport due to its interest and complexity in understanding the transport behaviour. Till date, more research are being conducted as the well-known conventional rotary drilling method used in drilling onshore reservoirs are now replaced by coiled tubing drilling, casing drilling, etc., due to the challenging frontiers encountered in recent deep and ultra-deep offshore reservoirs. To better understand the various mechanisms affecting cuttings transport in horizontal wellbores, many investigators have conducted various studies under varying conditions by employing different approaches as follows: experimental, numerical simulation, mathematical modelling and field case study. The factors affecting cuttings transport in horizontal wellbores have been critically reviewed and addressed. It is believed that cuttings transported in the annulus are not always affected by a single parameter but a combination of parameters to ensure efficient hole cleaning. This study is aimed at reviewing all available literature on two-phase cuttings-liquid transport in horizontal annular wellbores where conventional drilling fluids such as pure water, water-based muds and oil-based muds are used in the drilling process.

2 Factors Affecting Cuttings Transport

Cuttings transported through the annulus (hole–pipe geometry) are affected by series of drilling parameters. The study of the effects of these parameters has been a subject of research by several investigators over the decades. According to these investigators, the factors affecting cuttings transport in the wellbore can be summarised as but not limited to: annular fluid velocity (flow rate), drill pipe eccentricity, wellbore size (annular size), drilling fluid rheology (density, viscosity, yield point, gel strength), cuttings size, drill pipe rotation, drilling rate (rate of penetration), hole inclination, mud type, temperature and drilling fluid density. Overestimation or underestimation of these parameters may result in hole problems such as cavings, enlargements, closures, mud cake formation and excessive cuttings bed as depicted in Fig. 1. Therefore, there is the need to optimise these parameters for effective hole cleaning.

Reference [1] has illustrated in Fig. 2 that the practical use of these factors in controlling cuttings transport is much dependent on their controllability in the field.

2.1 Effect of Annular Velocity (Flow Rate)

Figure 2 indicates that flow rate has the most significant influence on cuttings transport and hence could be easily controlled. Both experimental studies and numerical simulations of cuttings transport have shown that higher flow rates result

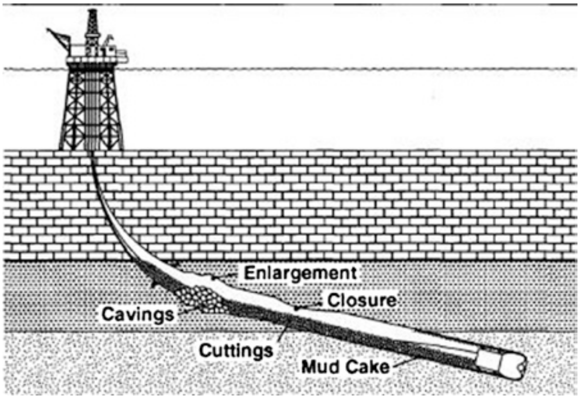

Fig. 1 Hole problems in high-angled wellbores

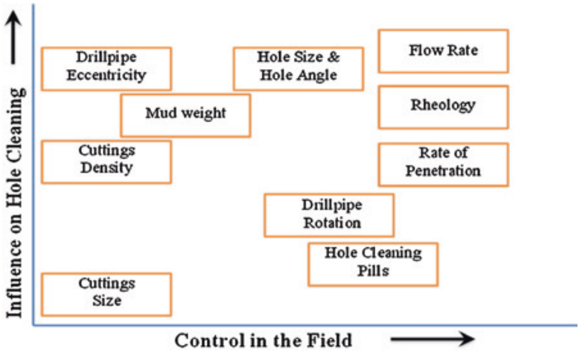

Fig. 2 Key variables controlling cuttings transport (modified after [1])

in drastic cuttings bed erosion [1–11]. Reference [12] observed that increasing flow rate of high-viscosity high-density sweep or high-viscosity sweep has no significant improvement on cuttings bed erosion. In addition, [13] observed a decrease in the critical flow rate required to reduce cuttings bed height as the open flow area decreases.

2.2 *Effect of Drilling Fluid Density*

Drilling fluid density or mud weight determines the cuttings carrying capacity. Mud weight is illustrated in Fig. 2 as one of the influential parameters on hole cleaning which could be moderately controlled on the field. Studies [5, 6, 14, 15] have shown that increase in fluid density enhances cuttings bed erosion and also prevents borehole collapse [16]. At high mud weight, the frictional effect of cuttings on rotating drill pipe also reduces [17]. Reference [18] indicated that fluid density is only a secondary factor in cuttings transport at constant critical flow rate.

2.3 Effect of Drilling Fluid Rheology

Fluid rheology also plays great role on hole cleaning as observed from Fig. 2. Experimental studies [19, 20] have shown that cuttings bed formation in high-viscosity fluids in laminar flow is slow compared low-viscosity fluids in laminar flow. On the contrary, other investigators [21, 22] have also observed that low-viscosity muds perform better than high-viscosity muds, whereas low-viscosity muds which are pumped in turbulent flow are more effective in hole cleaning than high-viscosity muds in laminar flow [23]. Furthermore, low-viscosity muds transport more large-sized cuttings than small-sized cuttings [24]. In addition, [12] noted that high-viscosity sweeps in the absence of drill pipe rotation is ineffective in cuttings bed erosion and cuttings removal, whereas low-viscosity sweeps with drill pipe rotation and improves 'sweep' efficiency at high flow rates. The effect of mud viscosity on cuttings transport however diminishes as drill pipe rotation speed increases [10].

On the other hand, a decrease in flow behaviour index, n, results in a decrease of stationary bed, whereas moving bed layer increases [25]. Reference [1] also observed that the increase in the ratio of flow behaviour index to consistency index (n/K) reduces cuttings bed height. Less gel strength formation in muds also helps minimise cuttings bed consolidation [16]. The mud yield point (YP) and plastic viscosity (PV) also influence cuttings removal. Further study [12] has shown that increase in YP at constant flow rate without drill pipe rotation results in negligible cuttings bed erosion, while a reduction in PV and YP results in a better hole cleaning at reduced flow rates [22].

2.4 Effect of Cuttings Size

The size of cuttings is mostly dependent on the type of formation being drilled as well as the type of drill bits. This parameter, as shown in Fig. 2, is very difficult to control. A general observation made by previous studies [3, 6, 23] shows that large-sized cuttings result in an increase in cuttings bed height. However, smaller-sized cuttings are observed to be more difficult to clean when using water as drilling fluid [8, 23] and, thus, require a higher flow rate to reach the critical transport fluid velocity (CTFV) due to their high interface interaction coefficient when using non-Newtonian fluids [21, 26, 27].

2.5 Effect of Drill Pipe Rotation

The rotation of drill pipe during drilling operations is shown to moderately influence hole cleaning and can be controlled as well (see Fig. 2). According to [19], drill pipe rotation has minor influence on cuttings transport when flow is turbulent. Higher drill pipe rotation speed is also observed effective in decreasing annular cuttings concentration at low flow rates and diminishes at high flow rates [9, 24, 28]. Cuttings bed erosion is greatly improved by drill pipe rotation once drilling operation is stopped [24]. Reference [29] observed that drill pipe rotation enhances better hole cleaning when high-density sweep is used, whereas at low-viscosity sweep, a considerable decrease in cuttings bed erosion is noted as drill pipe rotation increases [12]. Another investigator [30] also noticed greater impact of drill pipe rotation in transporting smaller cuttings sizes. However, other studies [9, 28] observed a slight decrease in cuttings moving velocity; hence, a negligible change in cuttings bed height as drill pipe rotation increases.

2.6 Effect of Drill Pipe Eccentricity

Eccentricity shows how drill pipe is displaced either towards the upper or lower part in horizontal wellbores. The influence on cuttings transport is extremely high, but it is also very difficult to control as depicted in Fig. 2. Studies [14] have shown that concentric annuli promote more cuttings bed erosion than eccentric annuli. In addition, others [3, 5, 15] also confirmed that an increase in eccentricity increases cuttings bed.

2.7 Effect of Annular Size

Annular size shows huge influence on cuttings transport as illustrated in Fig. 2. Experimental studies [31] have shown that increase in diameter ratio (a ratio of drill pipe diameter to hole diameter) improves hole cleaning due to the increase in annular velocity and wall shear stress.

2.8 Effect of Fluid Type

Reference [13] noticed that water, as a drilling fluid, is more effective for cuttings bed erosion, while PAC fluid is more effective in preventing cuttings bed formation. Meanwhile, PAC solution is also seen to improve the transport of small-sized cuttings than large-sized cuttings [8].

2.9 Effect of Drilling Rate (Rate of Penetration, ROP)

Several investigators [6, 9, 30] and [32] have illustrated that higher drilling rates generate more cuttings in the wellbore and hence results in higher cuttings bed height. This effect further increases the hydraulic requirement for effective hole cleaning [19, 24].

2.10 Effect of Temperature

Very few experimental studies [12, 33] have been conducted in recent times under elevated temperature to analyse its effect on cuttings transport. It can be ascertained from these studies that an increase in temperature results in a decrease in cuttings bed height with time when using both water and non-Newtonian fluids. Other observation is that the rheology of drilling fluids changes significantly with temperature, which affects the viscous drag forces applied on drilled cuttings [33].

3 Drilling Hydraulic Programmes

The complexity of cuttings transport, which involves the combination of interacting variables, would not make it prudent to solely rely on predictive models with limited boundary conditions. In this regard, many investigators have recommended some general operational guidelines based on the results from laboratory study as well as field experience and observations. Appendix A summarises these operational guidelines in Tables 1 and 2.

4 Conclusion

A comprehensive study on the factors affecting cuttings transport in horizontal wellbores has been presented. The most important factor controlling cuttings transport or hole cleaning is annular velocity as illustrated in Fig. 2. Fluid rheological properties and density have moderate influence, whiles cuttings size, annular gap, drilling rate, drill pipe eccentricity and rotation have slight effect on cuttings transport. It is evident that different authors had different opinions on specific drilling parameter effects. This could be attributed to the range of composition of parameters as well as experimental and numerical set-up range used in their respective studies. This review clearly shows that effective hole cleaning is not dependent only on a single drilling parameter but also on a combination of parameters. Qualitative hydraulic programmes for ensuring efficient hole cleaning and wellbore stability as proposed by other investigators are also presented.

Appendix

See Tables 1 and 2.

Table 1 Drilling hydraulic programme (modified after [34])

1.	Monitoring the torque and drag trends, the rate of cuttings returned and volume reduction of the active mud system as the hole is drilled provide a good understanding of how well the hole is being cleaned. This, in turn, helps improve drilling performance
2.	When penetration rate exceeds 100 fph (average), 24-h wellsite drilling engineering support is needed
3.	Monitoring the rate of cuttings return over the shaker is a simple but effective way to enhance the understanding of how the hole is cleaned under various operating modes
4.	Monitoring the reduction in the volume of the active mud system as the hole is being drilled is means of determining how the hole is cleaned under various operating modes
5.	Convergence and divergence trends of pickup and slack-off drill string weight can be used as a means to determine hole cleaning over a period of time
6.	A reduction in off-bottom rotating torque, under some conditions, may be an indication that the hole is loading up with cuttings
7.	Predicted and actual drill string weight may not be close if there is significant formation ledging

Table 2 Drilling hydraulic programme (modified after [35])

1.	Design the well path so that it avoids critical angles in possible
2.	Use top drive rigs, if possible, to allow pipe rotation while tripping
3.	Maximise fluid velocity, while avoiding hole erosion, by increasing pumping power and/or using large diameter drill pipes and drill collars
4.	Design the mud rheology so that it enhances turbulence in the inclined/horizontal sections, while maintaining sufficient suspension properties in the vertical section
5.	In large diameter horizontal wellbores, where turbulent flow is not practical, use muds with high suspension properties and muds with high metre dial readings at low shear rates
6.	Select bits, stabilizers and bottom hole assemblies (BHAs) with minimum cross-sectional areas to minimise ploughing of cuttings while tripping
7.	Use various hole cleaning monitoring techniques including a drilled cuttings retrieval rate, a drilled cuttings physical appearance, pressure while drilling and a comparison of pickup weight, slack-off weight and rotating weight
8.	Perform wiper trips as the hole condition dictates

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