Review and Analysis of Cuttings Transport in Complex Structural Wells

Wang Kelin*, Yan Tie, Sun Xiaofeng, Shao Shuai and Luan Shizhu

College of Petroleum Engineering, Northeast Petroleum University, Daqing 163318, China

Abstract: Complex structural wells are widely used in the development of marine oilfields, old oilfield sand low permeable oilfields. However, poor hole cleaning often occurred in the highly-deviated sections and horizontal sections of the complex structural wells, which affects rate of penetration, cementing quality and downhole safety. It is advisable to study the behavior of cuttings transport under different conditions. In general, experimental observations and CFD simulations are main methods to analyze the effects of cutting parameters, fluid parameters and operational parameters on hole cleaning. The correlations and models are applied to predict the number of cuttings and the critical velocity in the annulus. In this paper, an analysis of key parameters is conducted on cuttings transport, the existing problems and characteristics of these correlations and models are summarized,, and different removal methods of annular cuttings and future research needs are discussed. Although major improvements have been achieved in the past several decades, how to accurately predict the cuttings bed height, critical velocity and other key parameters, and to effectively solve the poor hole cleaning still is a difficulty challenge. Therefore, more research will be conducted to further understand cuttings transport mechanism in multi-factors coupling and complex wellbore conditions.

Keywords: cuttings transport, hole cleaning, cuttings removal method, complex structural well.

1. INTRODUCTION

Complex structural wells, including extended reach wells (ERW), horizontal wells, highly-inclined wells, a etc are widely used in the development of marine oilfields, old oilfields and low permeable oilfields. However, during drilling operations, if the fluid velocity is lower than a critical value in annulus, cuttings will accumulate and develop cuttings bed. In this case, poor hole cleaning results in higher drag and torque, pipe sticking, slower rate of penetration (ROP), formation fractures, bad cementing quality and wellbore steering problems. For example, in drilling Long 40-1 highly-inclined well of Sichuan Oilfield, hole cleaning problems resulted in more than one pipe sticking, and the drill string was jammed in 2288.87m [1]. The poor hole cleaning also happened in the 8 $^{1}/_{2}$ inch section of extended reach well in BP's Wych Farm Oilfield [2]. However, the average stuck pipe cost per well amounted to 1.7 million dollars for each well drilled between 1985 and 1988 [3]. As a result, cuttings transport has continued to be a subject of interest to researchers and engineers, and the research mainly focused on the sensitivity analysis, correlations and models, and cuttings removal methods. These achievements were mainly addressed in this paper.

2. ANALYSES OF KEY PARAMETERS ON CUTTINGS TRANSPORT

The major parameters which affect cuttings transport can be divided into three different groups [4]. The first group consists of cutting parameters such as cutting density, cutting shape and size, and cutting concentration. The second group consists of the fluid parameters i.e. fluid viscosity, fluid density, and fluid flow rate. The third group consists of the operational parameters including inclination, drillpipe rotation speed, annuli size, and eccentricity. Initially, experiments are the main ways to study the effects of these parameters on cuttings transport, and some universities and research institutions such as Tulsa University Drilling Research Projects (TUDRP) [5], Southwest Research [6], M.I. Drilling Fluids [7], Middle East Technical University (METU) [8] have established cuttings transport flow loops. In recent years, CFD [8] has also been used to simulate the cuttings transport in different conditions, help the researchers get to the root of problems and provide enough information where measurements are either difficult or impossible to obtain.

2.1. Effect of Drillpipe Rotation on Hole Cleaning

In rotary drilling, the drill pipe is always in rotation, except when making a connection or tripping. In the eccentric annuli, pipe rotation drives solid and liquid phase helical motion, and continously carries energy to these cuttings near the pipe surface, where cuttings slide along the rotary direction. Meanwhile, these cuttings also carry energy to nearby cuttings. Finally, some cuttings are carried by high fluid flow, and others form a cuttings bed which has asymmetrical distribution along the circumference direction. The two magnitudes are mainly dependent on fluid flow rate and rotary speed, and are also affected by inclination, particle size, and other factors. As shown in Table **1**, cutting transport is made easier when the drillpipe rotation speed is controlled in a special range.

*Address correspondence to this author at the College of Petroleum Engineering, Northeast Petroleum University, Daqing 163318, China;
Tel: +860459-6503521; Fax: +860459-6503482;
E-mails: wwangkelin@163.com, wkl2370@163.com

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Table 1. Drillpipe Rotation vs Hole Cleaning

Source	Rotary Speed	Additional Factors	Methods	Conclusion
Wang *et al.* [1]	0-60 rpm	Flow rate	China Petroleum University, 13-6 cm	Pipe rotation significantly reduces the cuttings bed height in a low flow rate, but the pipe rotation has no significant effect cuttings bed in high flow rate.
Bassal [5]	unknown	Inclination, viscosity and cuttings size	TUDRP	Pipe rotation enhances hole cleaning more when the used mud has a higher viscosity with smaller cuttings sizes or for hole angle at 65 degrees, and at horizontal.
Sifferman and Becker [6]	0-60 rpm	Inclination, particle size, ROP	Southwest Research, 20.3-11.4 cm	Pipe rotation has the greatest effect on hole cleaning for small cuttings and low ROP at inclination near horizontal.
Sorgun [8]	0-120 rpm	Motion manner	CFD, 7.4-4.6 cm	The orbital motion decreases the critical velocity required to remove stationary cuttings bed totally. But drillpipe rotation has no an additional contribution to hole cleaning after a certain rotation speed.
Ozbayoglu *et al.* [9]			METU, 7.6-3.8 cm	
Peden *et al.* [10]	0-120 rpm	Eccentricity, hole size, fluid viscosity and velocity	Heriot-Watt U, 8.9-6.3 cm	Pipe rotation has a significant effect on the minimum transport velocity in medium or highly viscous fluids. In small annuli or positive eccentricity, pipe rotation contributes to cuttings transport.
Sanchez *et al.* [11]	0-175 rpm	Motion manner, flow rate and inclination	TUDRP, 20.3-11.4 cm	Good hole cleaning can be obtained in orbital motion or with high rotary speed at 90 degrees and low flow rates.
Bilgesu *et al.* [12]	0-60 rpm	Particle size	CFD, 15.2-8.9 cm	Drillpipe rotation can improve cutting transport more for smaller sized particles.
Duan *et al.* [13]	0-160 rpm		TUDRP, 20.3-11.4 cm	Pipe rotation improves the transport efficiency of smaller cuttings compared with larger-sized cuttings.
Li *et al.* [14]	0-200 rpm		CFD, 21.6-12.7 cm	Pipe rotation between 80-120 rpm has a significant effect on hole cleaning.

2.2. Effect of Mud Rheology on Hole Cleaning

Rheology can be defined as the science of deformation and flow; it refers to the different properties and characteristics of the drilling fluid. These properties of the circulation fluid have an effect on solids transport. As shown in Table **2**, the rheology may include yield values, yield point/plastic viscosity (YP/PV), viscosity, fluid behavior index (n), and consistency coefficient (k). The rheology is related to shear force which mainly suspends and carries cuttings. However, the effect of rheology on cuttings transport depends on flow rate, flow regime and inclination. It is worth mentioning that low viscosity drilling fluid is effective to erode cuttings bed, but high viscosity contributes to carrying cuttings.

2.3. Effect of Inclination on Hole Cleaning

In the wellbore of complex wells, inclination may vary from vertical to horizontal. As shown in Table **3**, there is a range of inclinations where cuttings transport is the toughest, and the entire wellbore is divided into three segments based on cuttings transport mechanism. The former can help the designer to avoid the regions in designing the well path, but there is no precise range due to different experimental conditions. The latter can make these existing models and correlations of cuttings transport used for reasonable sections, and improve the accuracy of cuttings bed height and critical velocity. Therefore, it is necessary to evaluate the cuttings transport in different inclinations.

2.4. Effect of Cuttings Size on Hole Cleaning

To simplify experimental observation, cuttings are usually considered as uniform size. The cuttings size is related to their dynamic behavior in a flowing media. The terminal velocity, drag force, buoyant forces and shear forces between cuttings are affected by both the properties of the cuttings and the circulated fluid. As shown in Table **4**, some contradictory conclusions were reached due to different particle sizes, circulating fluids and other parameters, but it can be sure that pipe rotation and fluid rheology were the key factors in controlling small cuttings transport, and large cuttings transport is mainly dominated by fluid flow rate.

3. CUTTINGS TRANSPORT CORRELATIONS AND MODELS

Through experimental observations and CFD simulations, we can better observe and understand the cuttings transport process. To describe cuttings transport efficiency quantitatively, a large number of correlations and models were developed, and two types of parameters were used as target variables. The first type indicates the amount of annular cuttings under a given drilling condition, and can be calculated by annular cuttings correlations and models. The second type shows the required annular velocity to keep a minimum a amount of cuttings in a well, and can be obtained from the annular critical velocity correlations and models.

3.1. The Correlations and Models of Annular Cuttings

The amount of annular cuttings can clearly reflect the cuttings transport efficiency. In previous studies, cuttings bed height (**CH**), cuttings concentration (**CC**), cuttings bed area (**CA**), and the ratio between mass of suspended particles and initial mass of deposited cuttings (**RMC**) can be used to

Table 2. Mud Rheology *vs* Hole Cleaning

Source	Factors	Methods	Conclusions
Seeberger *et al.* [7]	Shear viscosity	M.I. Drilling Fluids	Low shear viscosity should be evaluated to obtain good hole cleaning.
Okrajni and Azar [15]	yield values and YP/PV	TUDRP, 12.7-4.8 cm	In laminar flow, higher mud yield values and YP/PV provide better cuttings transport. Cuttings transport was not affected by mud rheology in turbulent flow.
Hareland *et al.* [16]	Viscosity, YP/PV	TUDRP, 12.7-5.4 cm	YP/PV is detrimental to cuttings transport, and water-based mud has better hole cleaning than oil-based mud for medium and high inclinations.
Meano [17]	Yield stress	TUDRP	A decrease in cuttings concentration with increasing yield stress.
Kelessidis and Bandelis [18]	Viscosity	Technical University of Crete, 7-4cm	Raising viscosity of the drilling fluid deteriorates hole cleaning, because type of flow regime changes from turbulent flow to laminar flow; and it has been proved that cuttings can be better displaced in turbulent flow than laminar flow.
Ford *et al.* [19]		Heriot-Watt U, 8.9-6.1 cm	Improvement in hole cleaning occurs as viscosity increases.
Valluri *et al.* [20]		TUDRP, 14.6-8.9 cm	Water is very effective in bed erosion process, but it doesn't carry cuttings for a long distance.
Walker and Li [21]		BJ Services, pipe	Hole cleaning is more efficient with a low viscosity fluid in turbulent flow for horizontal/near horizontal wellbore, or with a high viscosity fluid in laminar flow for the vertical/near vertical wellbore.
Rishi *et al.* [22]	n/K	TUDRP, 20.3-11.4 cm	Lower cuttings bed height is achieved as the n/K ratio increases.
Ali *et al.* [23]	Plastic viscosity	University Technology Malaysia, 6.4-5.1 cm	Increasing the plastic viscosity of the mud results in a remarkable raise in the amount of recovered cuttings, but the surplus amount of viscosity inverses the result.

depict the amount of annular cuttings. The following models can be used to calculate these parameters:

Two layer model. The model, which is comprised of suspended layer, stationary or mobile cuttings bed, includes a stable two layer model (**STM**) and an unstable two layer model (**UTM**). As shown in Table **5**, these models have gradually considered the key factors, including cuttings distribution of the suspended layer, slippage between fluid and cuttings, particle settling, cuttings-fluid interaction, gain/loss from crumbling, cave-in of wellbore, and cuttings exchange between layers. However, there exist the following shortcomings in these

Table 3. Inclination *vs* Hole Cleaning

Source	Inclination	Methods	Conclusion
Sifferman and Becker [6]	45-90°	Southwest Research, 20.3-11.4cm	Cuttings bed may slide continually and tumble down at inclination between 45 and 60°. At angles from 60 to 90°, cuttings beds are quiescent, with little sliding or tumbling tendency.
Seeberger *et al.* [7]	unknown	M.I. Drilling Fluids	Cuttings bed problems rise at inclination angles between 35 and 55°.
Peden *et al.* [10]	0-90°	Heriot-Watt U, 8.9-6.3 cm	Hole angles between 40° and 60° are the worst angles for cuttings transport for both rolling and suspension transport form.
Okrajni and Azar [15]	0-90°	TUDRP, 12.7-4.8 cm	Cuttings are harder to be transported at 45-55° angle.
Ali *et al.* [23]	60-90°	University Technology Malaysia, 6.4-5.1 cm	A stationery cuttings bed can form for high angles transport. In intermediate angles, moving cuttings bed can form. At near-vertical angles, particle settling determines transport.
Yang *et al.* [24]	0-90°	Daqing Petroleum Institute	The critical angle is between 40 and 55°, and the highest cuttings concentration is presented from 45 to 60°.
Brown *et al.* [25]	0-90°	BP Research Centre, 20.3-12.7 cm	The poorest removal rates generally occur with angles in the region of 50 to 60 degrees.
Zamora and Hanson [26]	unknown	M.I. Drilling Fluids	The zones where cleaning is most difficult are between 30 and 60°.
Becker *et al.* [27]	30-70°	TUDRP	For inclination from vertical to 45°, transport performance is better when mud is in laminar flow. For inclination>60°, turbulent flow is recommended.
Mishra [28]	60-90°	CFD, 15.2-8.9 cm	As the deviation angle decreases, it becomes harder to clean out particles. Also, angle has the greatest influence on hole cleaning.

Table 4. Cuttings Size *vs* Hole Cleaning

Source	Particle Size	Methods	Conclusions
Wang *et al*. [1]	3.4-5.65 mm	China Petroleum University, 13-6 cm	In horizontal section, cuttings size have a minor effect on cuttings transport.
Ali [4]	2.54-6.99 mm	CFD, 20.3-10.2 cm	Cuttings transport for small particle size is greatly enhanced when drilling with high density mud circulated at high flow rate.
Bassal [5]	2 - 7 mm	TUDRP	Smaller cuttings are slightly harder to clean out.
Peden *et al*. [10]	1.7 to 3.35 mm	Heriot-Watt U, 6.3-8.89 cm	Smaller cuttings were more difficult to transport at any inclination with low viscosity fluid. While larger cuttings were easier to transport at low angles with high viscosity fluid.
Sanchez *et al*. [11]	2 to 7 mm	TUDRP, 20.3-11.4 cm	At high rotary speed and with high viscosity mud, the smaller cuttings are easier to transport.
Duan *et al*. [13]	0.45-3.3 mm	TUDRP, 20.3-11.4 cm	Smaller cuttings is more difficulty to be removed than larger cuttings when tested with water. But it has a opposite effect with 0.25 ppb PAC solutions.
Walker and Li [21]	0.15- 7 mm	BJ Services, pipe	An average size of 0.76 mm is most difficulty to be removed by the water.
Mishra [28]	3-8 mm	CFD, 15.2-8.9 cm	Hole cleaning is easier for larger particles as compared to smaller ones when water is used as the drilling fluid.
Martins *et al*. [29]	2-6 mm	Petrobras, 12.7-10.2 cm	Larger particles are always harder to be transported than smaller ones.

models: i) Pipe rotation is ignored. ii) Cuttings size, sphericity and distribution are uniform. iii) Cuttings bed concentration, ROP, mud density and rheological properties are constant. iv) An isothermal process is assumed. v) Mass and energy exchange between wellbore and formation.

Three layer model. The model, which is comprised of suspended layer, stationary and mobile cuttings bed, includes a stable three layer model (**STHM**) and an unstable three layer model (**UTHM**). As shown in Table **6**, these models have gradually considered the key factors, including cuttings distribution of suspended layer, particle settling, and mass exchange between layers. However, there exist the following shortcomings in these models: i) Mechanical equilibrium is used to calculate the cuttings bed velocity. ii) Cuttings size, sphericity and distribution are uniform. iii) Mud density and rheological properties are constant. iv) An isothermal process is assumed. v) Mass and energy exchange between wellbore and formation.

Three segment model. Cho *et al*. [42] established the first three-segment model, and the wellbore is divided into three segments (0-30°, 30-60°, and 60-90°). The vertical model, two layer model and three layer model were used to depict the 0-30° section, 30-60° section, and 60-90° section, respectively. Therefore, the accuracy of model is mainly dependent on both two layer and three layer model.

Empirical correlations. As shown in Table **7**, the correlations were developed based on the data from CFD and

Table 5. Two Layer Models of Cuttings Transport

Source	Goal	Model Type	Characteristics/Main Factors	Applicability
Lu [2]	CH	STM	The formation of cuttings bed in new drilling section.	Inclined well
Gavignet and Sobey [30]	CH	STM	Mud rheology, eccentricity, inclination.	Highly deviated well
Santana *et al*. [31]	CH	STM	Slippage between cuttings and drilling fluid.	High angle and horizontal well
Martins and Santana [32]	CC	STM	Diffusion equation.	Horizontal and near horizontal well
Kamp and Rivero [33]	CH	STM	Cuttings settling and resuspension, particle settling velocity.	Highly inclined well
Martins [34]	CH	UTM	Gain/loss from crumbling, cave-in of wellbore.	ERW
Li *et al*. [35]	CH	UTM	Exchange of particle and drilling fluid between layers.	Horizontal well
Doan *et al*. [36]	CC CH	UTM	Cuttings deposition and resuspension, formation, interaction between fluid phase and solid phase in suspended layer, and interaction between cuttings bed and suspended layer.	Highly-inclined well
Suzana *et al*. [37]	CH	UTM	Solid-liquid interaction, slippage between fluid and cuttings, mass diffusion, cuttings mass flow between bed and suspension.	0-90°

Table 6. Three Layer Models of Cuttings Transport

Source	Goal	Model Type	Characteristics/Main Factors	Applicability
Lu [2]	CH	STHM	The formation of cuttings bed in new drilling section.	Inclined well
Nguyen and Rahman [38]	CH	STHM	Effective thickness expression	Deviated and horizontal well
Cho *et al*. [39]	CH	STHM	Diffusion equation, particle settling, changing ROP.	Horizontal well
Ozbayoglu *et al*. [40]	CA	STHM	Slip between fluid and cuttings, in- situ concentration of flowing cuttings.	Highly-inclined well
Wang *et al*. [41]	CH	UTHM	Suspension, rolling, slipping, or all these forms together, drillpipe rotation, mass exchange between layers.	ERW

experiments. Flow rate, ROP, annuli size, inclination, mud density and rheology, eccentricity, pipe rotation and other parameters were considered. These correlations can provide the simplified algorithm for the engineering and check the accuracy of the above mechanical models, but it is limited in narrow regions.

3.2. The Correlations and Models of Annular Critical Velocity

To assure the safe and efficient drilling, the reasonable choose of flow rate and accurate prediction of critical velocity are very important. In these studies, critical transport fluid velocity (**CTFV**), critical flow rate (**CFR**), minimum transport velocity (**MTV**), critical resuspension velocity (**CRV**), minimum flow rate (**MFR**), and critical flow velocity (**CFV**) are used to depict the critical velocity. All of these pertain to the same condition, which is defined as the minimum average annular fluid velocity to prevent the formation of cuttings bed, and there are two methods to calculate the critical velocity.

Mechanical model (MM). As shown in Table **8**, there are two types used to calculate critical velocity. The first type is obtained by establishing mechanical equilibrium among static force, drag force, friction forces, lift force, Van der Waals force, plastic force and pressure force. The second type is obtained by mass balance between cuttings generated and transported. The common problem of the two is how to accurately determine these coefficients, including drag coefficient, lift coefficient and inclination factor.

Empirical correlations (EC). Similar to the empirical correlations of annular cuttings, as seen in Table **8**, these correlations considered flow rate, ROP, annuli size, inclination, mud density and rheology, etc, but they are valid under special conditions.

4. CUTTINGS REMOVAL METHODS

High fluid velocity. A well-known solution to solve hole cleaning problem is to increase the flow velocity of the drilling fluid, which can decrease cuttings concentration in the annuli. However, on one hand, a high fluid flow velocity is limited by surface equipments and downhole drill string. On the other hand, the increment of the annular fluid velocity results in open hole erosion and uncontrolled losses after fracturing. This is particularly true in deep water drilling where only a narrow mud window is available. For example, the cuttings transport experiments of high fluid velocity were conducted in the Li 1-11 well. Good hole cleaning was achieved when flow velocity varied from 32-35 L/s to 60 L/s, but soft formation appeared crumbling and cave-in due to higher flow velocity [51].

Drilling-fluid additives. Over the years, various methods have been introduced to control the formation of cuttings beds. Most of these methods change the rheology of drilling fluid, such as YP/PV, n and viscosity (Table **2**), which enhances the cuttings-transport ability of the drilling fluid. Unfortunately, these methods are inefficient in completely preventing the formation of a cuttings bed, and cause additional problems. For horizontal and highly deviated sections, fiber sweep can be applied to clean the borehole and reduce cuttings bed height. Some field applications were also conducted, and made some

Table 7. Empirical Correlations of Annular Cuttings

Source	Goal	Characteristics/Main Factors	Applicability
Wang *et al*. [1]	CH	Flow rate, injection rate of cuttings, mud density and viscosity, eccentricity, pipe rotation.	Horizontal well
Bassal [5]	CH	Flow rate, ROP, rotation speed, mud density and rheology, annuli size, cuttings size and density, inclination.	Inclined well
Li *et al*. [14]	CH		ERW
Ozbayoglu *et al*. [9]	CA	Flow rate, ROP, annuli size, inclination, mud density and rheology, pipe rotation, eccentricity	Horizontal and deviated well
Duan *et al*. [13]	CC/CH	Flow rate, hole angle, cuttings size, and pipe rotation.	ERW
Loureiro *et al*. [43]	RMC	Annuli size, cuttings density, local gravity, mud density and rheology, rotation speed, initial cuttings bed height and mass	Horizontal well
Ozbayoglu *et al*. [44]	CA	Flow rate, ROP, annuli size, inclination, mud density and rheology.	Inclined-horizontal well

Table 8. Mechanical Correlations and Models of Critical Velocity

Source	Goal	Model Type	Characteristics/Main Factors	Applicability
Peden *et al*. [10]	MTV	MM	Drag force, friction force, gravity force and lift force.	Inclined well
Ozbayoglu *et al*. [44]	CFV	EC	Flow rate, ROP, annuli size, inclination, mud density and rheology.	Inclined-horizontal well
Clark and Bickham [45]	MTV	MM	Buoyancy force, the plastic force, gravity force, lift force, drag force and pressure force.	0-90°
Larsen *et al*. [46]	CTFV	MM	Mass generated by drillbit=mass transported by mud	55-90°
Duan *et al*. [47]	CRV	MM	Static force, drag force, lift force and Van der Waals force.	Horizontal and high-angle well
Luo *et al*. [48]	CFR	EC	Annular size, eccentricity, gravity, flow rate, inclination, fluid and cutting properties	Deviated well
Mirhaj *et al*. [49]	MTV	EC	Flow rate, ROP, rotation speed, mud density and rheology, annuli size, cuttings size and density, inclination.	Deviated and horizontal well
Mohammadsalehi and Malekzadeh [50]	MFR			0-90°

achievements [52-54]. However, the flow behavior, hydraulics, and cuttings-transport efficiency of fiber sweeps is less known, and the following conclusions were reached based on the experiments [20, 55-56]:

1. Adding fiber materials into drilling sweeps significantly improves sweep efficiency of the fluid in fully eccentric annuli, especially in the horizontal configuration. The effect of fiber is minimal at the 70° configuration.
2. High viscous and high density sweep is ineffective to carry cuttings.
3. The increment of fiber concentration improves the cleaning efficiency if the pipe rotation and/or flow rates are high. As greater amounts of fiber were employed, efficiency further decreased, unless combined with adequate pipe rotation or flow rate.
4. If fiber additives are employed in higher concentration under high flow rate conditions or with rapid rotation, cuttings removal will be increased relative to lower concentration sweeps under the same conditions.
5. It was noted that some decrease in sweep efficiency always accompanied the addition of fiber, given the fluid properties and inclination utilized for these tests.

Mechanical methods. Cuttings removal tools (CRT) as a mechanical method have helical grooves or blades on their surface. A negative angle is designed on each blade to improve the scooping effect of cuttings bed. The blades scoop the cuttings bed and help to bring the cuttings into suspension with drillpipe rotation. Meanwhile, these suspended cuttings are carried away by drilling fluid, which results in good hole cleaning. To further understand the interaction mechanism between tool and cuttings or drilling fluid, and study the performance of the tool in various conditions, the following conclusions were reached by experiments [57-59] and CFD simulations [60-61].

1. V-shape slot can make velocity field helical distribution and inlet velocity increase by around 100% in a very short axial distance.
2. fluid can form a vortex cavity near spiral grooves with CRT, and cuttings are transported by the vortex cavity from low side to up side.
3. The use of CRT can reduce the loss of velocity in the cuttings bed erosion better than standard equipment.
4. CRT can effectively remove the cuttings in highly deviated and horizontal well, but improves hole cleaning regardless of the bed area in horizontal well.
5. Bed area is sensitive to differences in tool spacing when a small number of tools per length of the wellbore is used.
6. The drillpipe rotation has a moderate effect on the performance of the CRT.

To date, the CRT have carried out some field tests [62-63], and developed some patents [64-65]. However, how to design a tool which is the integration of cleaning efficiency, time saving, operational safety, wellbore quality, low cost and rotary torque is still a difficult challenge.

5. FUTURE RESEARCHES

5.1. Improving Cuttings Transport Flow Loops

Even though many flow loops have been established over the past few decades, most of these flow loops can not depict the real cuttings transport in real wellbore conditions, such as formation fluid influx, wellbore collapse and wellbore heat transfer. Meanwhile, these facilities only can measure cuttings bed height or area and pressure, and can't record velocity field and concentration distribution of particles, which leads to poor accuracy of some coefficients and parameters referred by mechanistic models such as particle diffusion coefficient and hindered particle settling velocity, and affects the accuracy of mechanistic models. Ideally, CCD video camera system [43, 66] is introduced into flow loops to record the velocity profile, cross-sectional distribution and average velocity of cuttings. Also, a more realistic annular tested section should be considered to accord with the different downhole conditions.

5.2. Optimizing Mechanistic Models

There seems to be two main reasons for a low accuracy of most of mechanistic models. First, researchers attempt to establish the comprehensive models covering wide ranges (from vertical to horizontal), or use the same methodology for different physical phenomena that occur under different conditions. The other problem is to apply improper concepts, simplify too many assumptions or neglect certain observed phenomena [39]. However, there is a big difference between cuttings bed distribution and available models when the drillpipe is rotating, and a new theory or method will be introduced into mechanistic models. In addition, these problems as mentioned above will be gradually considered, and some high-accuracy coefficients can be obtained from the advanced flow loop.

5.3. Developing Cuttings Removal Technology

According to the above analysis of cuttings removal methods, fiber sweep and cuttings bed removal tool are considered as two effective methods to remove cuttings. Experiment and CFD will be continously applied to understand the cuttings removal mechanism and optimize fiber sweep and CRT, and field tests to check cuttings removal performance of the two. In addition, when and where to apply the two and how to use the combination of fiber sweep and CRT should be further studied.

5.4. Building Hole Cleaning Optimizing System

Hole cleaning is closely linked with both drilling design and drilling operations, and building a real-time hole cleaning optimizing system may be an indispensible part of automatic drilling. The system is composed of design system, data collecting system, data processing system and decision making system. Design system integrates the hole cleaning problem into hydraulics design, and eliminates critical inclination if possible. As drilling goes on, the data collecting system uses advanced instruments to rapidly collect the available data such as pipe rotation speed, pipe eccentricity, annular fluid flow rate. Subsequently, the system can obtain the real-time hole cleaning parameters such as cuttings bed height, cuttings concentration and hydraulic pressure drop by processing these collecting data. Finally, the decision making system conducts the comprehensive evaluation for hole cleaning conditions, and makes a quick decision whether measures are taken to improve cuttings transport and prevent downhole accidents, and which measure should be taken if necessary. Martins *et al.* [67] and Lapierre *et al.* [68] make such an attempt, but much more work is needed to built a comprehensive optimizing system.

6. CONCLUSIONS AND RECOMMENDATIONS

Based on extensive studies of cuttings transport and field experiences, the following suggestions are recommended to achieve better hole cleaning and cuttings transport when drilling complex structural wells.

1. Hole cleaning problem should be integrated into hydraulics design before drilling, and the critical angle should be avoided if possible.
2. If possible, top drive rigs and drilling fluid continuous circulation system can be used to maintain drillpipe rotation and drilling fluid circulation while tripping.
3. For highly deviated and horizontal sections, cuttings bed removal tool and fiber sweep can be considered.
4. Higher viscous drilling fluid with pipe rotation speed between 40 and 80 rpm can be used to erode the cuttings bed.
5. A larger drillpipe is recommended to increase flow rate, and highest mud weight possible is to increase buoyancy of cuttings.
6. Low viscosity drilling fluids for loose formation drilling and polymeric drilling fluids for hard formation drilling can realize efficient cuttings transport.
7. When adjusting drilling fluid performance, annular flow should be considered.
8. Solids control system will continue working to keep lower solid concentration and sand content.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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