A New Model of Cuttings Bed Height for Horizontal Small Bore Pipes without Rotating Drill-Pipe

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***Abstract* — Compared with conventional size, the horizontal small bore, usually termed slim hole, has great annular pressure drop due to very slim annulus, and cuttings transport characteristics are also different. To acquire the cuttings transport model for horizontal slim hole, an experimental study was carried out and several dimensionless variables were deduced. Then a cuttings bed height mathematical model was derived. The contrast analysis between calculation results of the model and experimental results from Martins' literature was made using the model, which showed that the model was more suitable for prediction of cleaning problems of horizontal slim holes, the results had a guiding significance for annular hole cleaning and hydraulic parameters design of horizontal small bore holes.**

Keywords - horizontal slim hole; cuttings transport; dimensional analysis; nonlinear regression; cuttings bed height

I. INTRODUCTION

With the development of drilling technology, interest has been growing in the drilling slim hole because it greatly reduces the drilling cost due to its smaller size equipment, and it is widely used marine oilfield, old oilfield and low permeable oilfield. But its annulus is slim and annular pressure drops are great, which causes the choice of range of flow rate is narrow. And the eccentricity of pipe decreases the annular velocity on the low side of the annulus, which leads to exacerbate the cuttings deposition. Cuttings are easy to collide each other and would be deposited into bed due to slim annuli in drilling slim holes. And downhole drilling tools are usually used rather than drill-pipe rotating which isn't conducive to suspension and transport for cuttings, so it is more difficult to hole cleaning for slim hole. The traditional cuttings transport models without considering hole dimensions are not precise to predict hole cleaning of slim hole, therefore, it is necessary to develop cuttings transport model of horizontal slim hole. To research the cuttings transport for horizontal slim hole, an experimental set-up of cuttings transport for horizontal slim hole was founded. And research on influence rule between different drilling parameters and cuttings transport was carried out and dimensionless cuttings bed height model for horizontal slim hole was investigated through dimensional analysis. It is expected that the results of this study will be useful to hole cleaning and hydraulic parameters design for horizontal slim hole.

II. LITERATURE OF REVIEW

Hole cleaning is still the key problem urgently to be solved for deviated, highly deviated and long reach drilling well. Since the past 50 years, scholars at home and abroad carried out a large amount of experimental research, theoretical analysis and numerical simulation to study hole cleaning. Some models such as critical annular velocity model, cuttings bed height model, cuttings bed area model and annular cuttings concentration model had been developed for trouble-free operation. Some were empirical models through experiment and numerical simulation. Others were theoretical models through annulus stratification theory. Where, the annulus could be divided into two layers or three layers according to cuttings distribution characteristics of annulus. These models had made significant progress in the prediction of hole cleaning and pushed the development of drilling technology. For example, Larsen et al.(1997) performed a large number of experiments and developed empirical models for the inclination between 55° and 90°. They concluded the minimum transport velocity (defined as the mean stream velocity required to prevent the accumulation of a layer of stationary or sliding particles on the bottom of a horizontal conduit) [1]. N. Malekzadeh (2011) obtained hole cleaning and minimum annular flow prediction method for the inclination between 0° and 90° based on Larsen model, with the help of computer iterative algorithm [2].

Ozbayoglu et al. defined a set of dimensionless parameters applying Buckingham-π theorem and obtained the influence law of drilling parameters to dimensionless annular cuttings bed area and critical annular velocity. The dimensionless annular cuttings bed area model was obtained by a large amount of experiment data regression analysis under the condition of drill-pipe fully eccentric but not rotating. The model was with an error less than 15% compared with field case data [3].

Duan et al.(2009) studied the influence of small-size cuttings to cuttings transport for large deviated wellbore and Critical Re-Suspension Velocity (CRV) model was obtained. And the Critical Deposition Velocity (CDV) correlations developed for large-size cuttings was corrected [4].

In addition, some scholars theoretically tried to derive cuttings transport model for horizontal wellbore, according to the results of experimental observation, the annulus was divided into two layers or three layers. Gavignet and Sobey first proposed the two-layer model of cuttings transport in theoretically by dividing borehole annulus into suspension layer and cuttings bed layer [5]. Kamp, etc. established two-layer model of hole cleaning for highly inclined wellbore on the basis of cuttings settling and suspension [7]. Suzana studied two-layer unstable transport model according to drift model on the basis of solid-liquid coupling effect for suspension layer [8]. Nguyen, etc. put forward three-layer cuttings transport patterns by dividing borehole annulus into homogeneous concentration of cuttings bed layer, changing concentration of dispersion layer and suspension layer, and gained the numerical solution according to mass and momentum conservation equation [9].

Many field cases confirmed that the hole size was also an important parameter influencing the cuttings transport, especially for horizontal slim hole because of its small annular gap between the drill-pipe and the drilled hole. Wall roughness involved the fluid resistance was very big and annular pressure loss was very big, which caused the hydraulic parameters of horizontal slim hole range very narrow. So existing cuttings transport models were not simply applied to hole cleaning, it should be aimed at cuttings transport study for horizontal slim hole. At present, few studies about cuttings transport for horizontal slim hole appeared in literatures.

To study cuttings transport rule of horizontal slim hole, Sang-Mok Han, etc. set up an experimental equipment of horizontal slim hole cuttings transport. Where, the outside diameter of the inner pipe and the inside diameter of the outer pipe were 30 mm and 44 mm, respectively, and the length of straight pipe upstream of the test section was 1.8 m. The mud systems which were utilized included aqueous solution of sodium carboxymethyl cellulose (0.2~0.4% CMC) and 5% bentonite solutions. The influence of annular velocity and drill-pipe rotation speed to solid volumetric concentration and annulus pressure drops were analyzed for the inclination between 0° and 70°. Fujii,etc. carried out annulus flow test of different section using water and CMC as fluid, and studied the cuttings transport velocity and migration characteristics using image processing technology[13]. Young-Ju Kim (2014) studied small-size cuttings transport characteristics in horizontal slim hole and established the annular cuttings concentration empirical equation[14].

III. CONCLUSION FOR CUTTINGS BED HEIGHT OF HORIZONTAL SLIM HOLE

It has been noticed that the cuttings bed height is relate to the following variables: flow rate, drill-pipe eccentricity, rate of penetration (ROP), wellbore angle of inclination, drilling fluids properties (rheology), drilling fluids density, cuttings size and borehole geometry size. So a stationary cuttings bed height in a wellbore can be summarized as

$$H = f\left(V, E, ROP, D_0, D_i, \rho, \mu_e, d_p\right) \tag{1}$$

Where H is dimensionless cuttings bed height (percentage).The meaning of parameters in formulas can be seen in nomenclature.

In order to develop a general and universal model valid for a wide range of drilling conditions, it is eminent to describe the variables influencing hole cleaning phenomena in terms of dimensionless groups. Thus, a dimensional analysis is conducted using independent drilling variables. The drilling variables in (1) is simplified and presented as

$$H = f\left(V, E, C_c, d_{hyd}, \rho, \mu_e, d_p\right) \tag{2}$$

Where $d_{hyd} = D_0 - D_i$,is hydraulic diameter and $C_C = ROP \,/\, R_T V\left(1 - \frac{D_i^2}{D_0^2}\right)$ is the cuttings volume concentration. R_T is cuttings transport ration and usually as 0.5.

The cuttings bed height of horizontal slim hole can be concluded through dimensionless analysis according to experimental data. The specific process is as follows: Since there are 8 independent variables and 3 basic variables among them, 5 dimensionless groups will be developed. After applying Buckingham-π theorem, dimensionless groups are determined as follows:

$$\Pi_1 = \frac{\rho V d_{hyd}}{\mu_e}, \Pi_2 = \frac{V^2}{g d_{hyd}}, \Pi_3 = C_c, \\ \Pi_4 = E, \Pi_5 = \frac{d_p}{d_{hyd}} \tag{3}$$

Where, Π_1 -the characterization of the ratio of inertia force and viscous force between the fluid that is the Reynolds number, Π_2 -the characterization of the inertial force and the effect of gravity on fluid that is the Froude number, Π_3 -cuttings volume concentration, Π_4 -the characterization of eccentricity influence on the shape of flow coefficient and Π_5 - characterize the effect of the particle size of the cuttings.

To conclude the mathematical model of the dimensionless cuttings bed height with five dimensionless variables, an experimental work was carried out.

IV. EXPERIMENTAL WORK

A. *Experiment Set-Up*

Experiments with cuttings transport were conducted on the China University of Petroleum Key Laboratory of Sinopec, as shown in Fig.1. It consists of an annular test section, cuttings injection system, cuttings separation system, drilling fluids circulation system, lifting system, and control system. The test casing string is 24 miles long, consisting of three section transparent glass tube (50.8mm ID) and an inner drill-pipe (25.4mm OD), yield a radius ratio of 0.5 for the annulus. To ensure fully developed flow in the measuring section, the length of straight pipe upstream of the test section is 12 m, corresponding to 472 hydraulic diameters. The drill-pipe lies in the lower side of the outer casing with an average eccentricity of 0.75. The drilling fluid is stored in a 2m^3 tank. The drilling fluid is agitated with a mixer driven by a hydraulic motor. The drilling fluid is pumped into the annulus by a centrifugal pump with a capacity of approximately 200 liter/min.

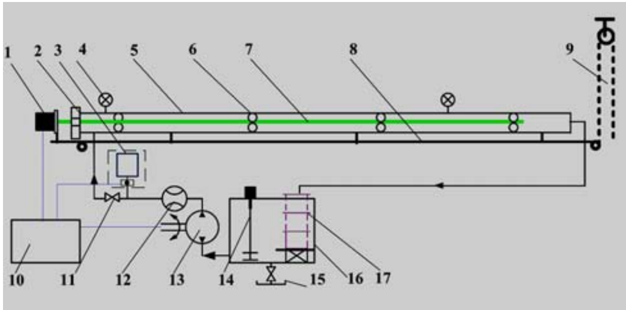

Fig.1 Schematic diagram of experimental apparatus for horziontal slim hole.

1.stepper motor 2. eccentric flange 3.cuttings inject system 4. pressure gauge 5.model wellbore 6. centralizer 7. model drill string 8. experimental stents 9. lifting system 10.control system 11. control valve 12. flow meter 13. centrifugal pump 14. agitator 15. recycling pool 16. storage tank 17. cuttings separation system

B. Experimental materials and experimental design

Since the modeling casing diameter is 50.8 mm and inner drill-pipe is 25.4 mm, the median diameters of sand-sized cuttings are respectively set as 1mm, 2mm, 3mm proportionally with density of 2550 kg/m^3 in this study. Annular fluid velocity ranged from 0.7 to 1.3 m/s. The rate of penetration(ROP) can be gained by cuttings injection velocity. According to inlet volume fraction of cuttings, a formula can be expressed as:

$$C_C = \frac{ROP}{R_T V\left(1-\frac{D_i^2}{D_0^2}\right)} = \frac{V_p\ /\ (60\rho_s)}{V\ \frac{\pi}{4}\left(D_0^2 - D_i^2\right)} \tag{4}$$

Where V_p is cuttings injection rate, kg/min, the V_p can be concluded as:

$$V_p = \frac{15\rho_s \cdot ROP \cdot D_0^2}{R_T} \tag{5}$$

Where ρ_s is cuttings density. When V_p is chosen as 0.137、0.274、0.548、0.823 kg/min respectively, then ROP is 2.5,5,10,15 m/h according to (5).

0.3~0.5% PAC solutions and 0.1~0.4% XC, as polymer materials, were added to water with a certain proportion to make up four water-based drill fluids. The rheological properties were shown in Table I tested through a six-speed viscometer. Seen from Table I, the first column is serial number of the drill fluids, the second-seventh columns are the values of the rheological properties.

In order to acquire the effective viscosity of drill fluid, the rheological model of the drill fluids should be concluded.

Table I. FOUR WATER-BASED DRILLING FLUIDS

NO.	$\phi 600$	$\phi 300$	$\phi 200$	$\phi 100$	$\phi 6$	$\phi 3$	n	k (Pa. s^n)
1	16.5	11	9	6	1.2	0.8	0.57	0.29
2	21	14	11	8	2	1	0.59	0.34
3	29	20	16	12	3.5	2	0.51	0.74
4	46	33	26	19	4	3	0.53	1.13

The law of the shear stress and shear strain based on the data in Table 1 is shown in Fig. 2. It can be seen from the diagram, the drilling fluid rheological properties made up by PAC and XC is suitable for the power law mode, namely, $\tau = k\gamma^n$. Where τ -shear stress, γ - shear strain, n - fluid behavior index and k -consistency index, $P_a \cdot s^n$. Then the drilling fluid effective viscosity could be gained according to (6):

$$u_e = k\left(\frac{2\cdot n+1}{3\cdot n}\right)^n \cdot \left(D_o - D_i\right)^{1-n} / \left(12\cdot V\right)^{1-n} \tag{6}$$

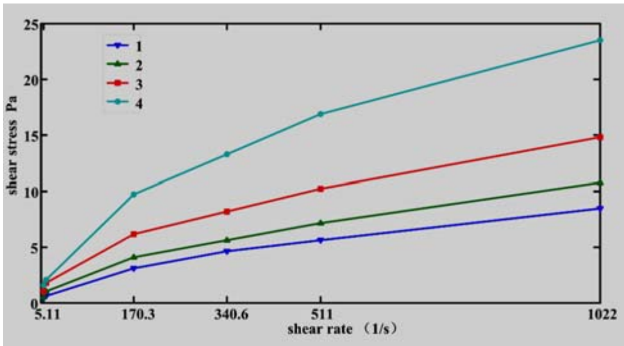

Fig.2 Drill fluid rheological properties

To study the influence rule of different drilling parameters to cuttings transport for horizontal slim hole, a parameter test matrix of cuttings transport was shown in Table II. The annular velocity was changed from 0.7-1.3 m/s with the step size of 0.1m/s. ROP , E have four different values and d_p , ρ have three different values.

V. RESULTS AND DISCUSSIONS

The relationship between the dimensionless group present in Equation 3 and the dimensionless cuttings bed height is analyzed, shown in Fig.3-Fig.6. The relation between Reynolds number and dimensionless cuttings bed height is shown in Fig.3, it can be seen that as Reynolds increases, a reduction is observed in the stationary bed height. This trend observed is due to the fact that, Reynolds number includes fluid velocity term, and the drag force applied on cuttings particles increases along the increase of fluid velocity, then the stationary cuttings bed decreases.

Table II. EXPERIMENTAL VARIABLES DESIGN OF THE SLIM HOLE

V (m/s)	ROP (m/h)	E	d_p (mm)	ρ (kg/m^3)
0.7	2.5	0	1	1000
0.8	5	0.25	2	1180
0.9	10	0.5	3	1250
1	15	0.75		
~1.3				

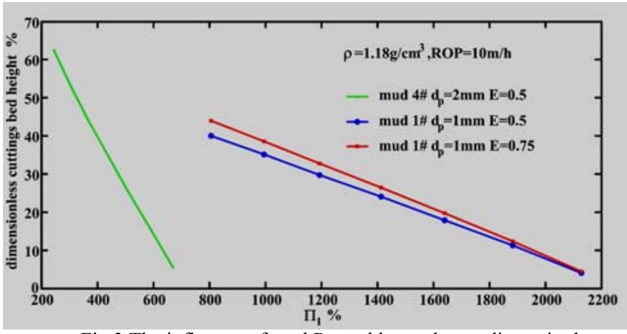

Fig.3 The influence of mud Reynolds number to dimensionless cuttings bed height

Fig.4 shows the relation between Froude number and dimensionless cuttings bed height. The dimensionless cuttings bed height decreases along the increase of Froude number for the selection of four kinds of fluids. It is due to the fact that Froude number is proportional to square of annular velocity. The annular velocity has great effect on cuttings bed height. As annular velocity increases, the Froude number increases, then cuttings bed height decreases.

The fluid properties have great effect on cuttings bed height. As the viscosity selected mud(from mud 1 to mud 4) increases, an increase is observed in the stationary bed height, so we should select lower viscosity fluid in drilling horizontal slim hole. The relation between drill-pipe eccentricity and dimensionless cuttings bed height is shown in Fig.5. When other parameters keep a constant, the more the drill-pipe eccentricity, the greater the cuttings bed height, it is because the eccentric annulus can be divided into broad and narrow clearance. Narrow clearance lies in the bottom of the annular gap, which causes its average flow velocity and fluid drag force acted on the particles more smaller and cuttings easy deposited. As also seen from the figure that the eccentricity under low velocity has more significant effect on cuttings bed formed due to the interaction between drill-pipe eccentricity and annular velocity.

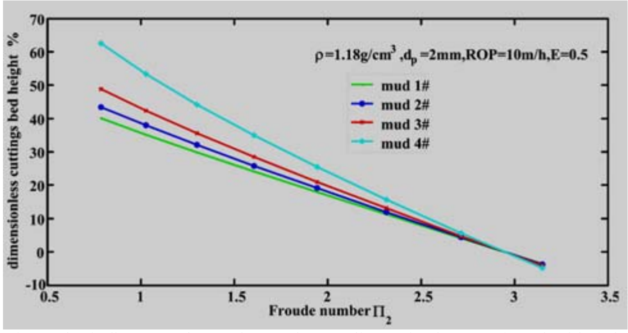

Fig.4 The influence of Froude number to dimensionless cuttings bed height

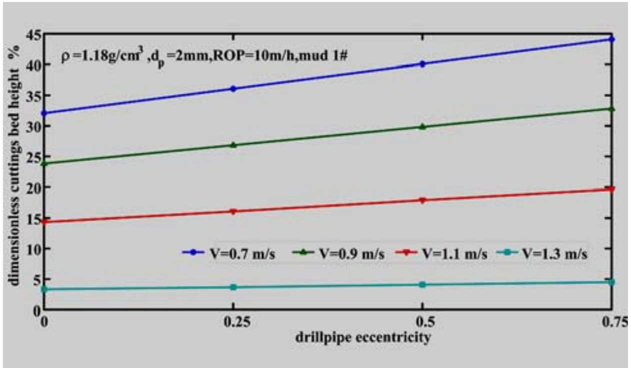

Fig.5 The influence of drill-pipe eccentricity for dimensionless cuttings bed height

The relation between cuttings volumetric concentration and dimensionless cuttings bed height is shown in Fig.6. It can be seen that the greater the cuttings volumetric concentration, the greater the dimensionless cuttings bed height. This is because the greater the cuttings volumetric concentration, the greater the friction between wall and cuttings particles or among cuttings, which reduces the cuttings transport ability, and makes the cuttings bed height increase

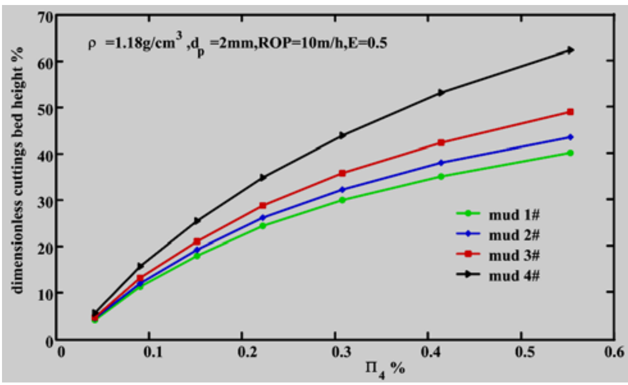

Fig.6 The influence of cuttings volumetric concentration for dimensionless cuttings bed height with different muds.

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The relation between annular velocity and dimensionless cuttings bed height for different cuttings particles diameters is shown in Fig.7. It can be seen from the figure that small size particles are easy to deposit because the small size cuttings are easy to gather, and cuttings concentration is greater, which increases the difficulty of cuttings transport.

Based on a great amount of experimental observation data, and through nonlinear regression analysis by means of Matlab, a proposed relation between the dimensionless groups and the dimensionless cuttings bed height is presented as

$$H = 197.35\left[\begin{array}{c}\left(\dfrac{\rho V\left(D_0-D_i\right)}{\mu_e}\right)^{-0.09}\left(\dfrac{d_p}{D_0-D_i}\right)^{-0.0087}\\ \left(1-0.294\dfrac{V^2}{g\left(D_0-D_i\right)}\right)\left(\dfrac{\rho_s-\rho}{\rho}\right)^{0.3}\\ \left(1+0.254E\right)\left(\dfrac{ROP}{V\left(1-\dfrac{D_i^2}{D_0^2}\right)}\right)^{0.18}\end{array}\right] \tag{7}$$

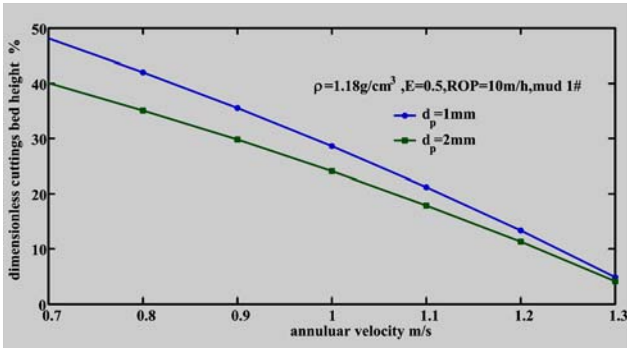

Fig.7 The influence of flow rate for dimensionless cuttings bed height with different cuttings diameter

To validate the concluded model, the predicted results computed by (7) are compared with the experimental data shown in Fig.8. It can be seen that the predicted results with the experimental measurement results are very close, and the fitting degree is 0.9815, which proves the accuracy of the prediction model.

VI. THE MODEL VALIDATION

In order to verify the reliability of dimensionless cuttings bed height calculation model of horizontal slim hole, a comparison was made with the results from Martins' experiment [15]. The selection of experimental parameters was following. Flow loop consists of 100-88.9 mm with fully eccentricity. The drilling fluid viscosity and yield stress are 10.8 $mP_a \cdot s$ and 6.9426 Pa, respectively. The drilling fluid density and cuttings particle diameter are 1000 kg/m^3 and 2.6 mm, respectively. It is shown from the Fig.9 that calculation results are less different but underestimating than Martins' experimental results, which is due to different wellbore size compared with experimental appliance and measure error. Particularly when annulus is divided as stable cuttings layer, mobile cuttings layer and suspension layer, the cuttings bed thickness of mobile cuttings layer is difficult to measure, which would cause a certain error.

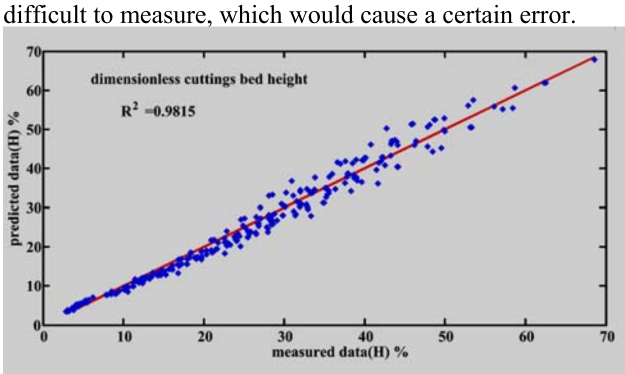

Fig.8 Predicted results versus experimental data

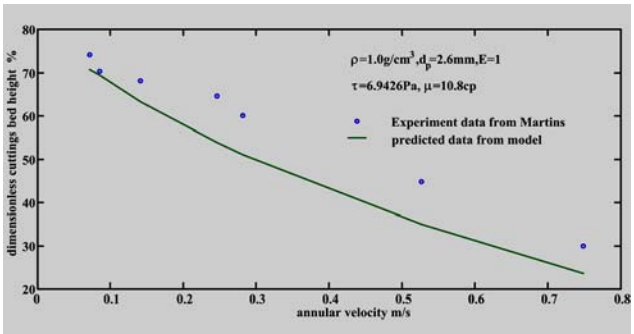

Fig.9 The influence of flow rate for dimensionless cuttings bed height comparison predicted data with martins' experimental data.

–VII. CONCLUSIONS

(1)Applying Buckingham-π theorem, five dimensionless groups have been developed, and a dimensionless cuttings bed height has been developed for horizontal slim hole.

(2) A horizontal slim hole cuttings transport experiment has been carried out. Based on a mass of experiment data, a cuttings bed height model formula of horizontal slim hole was concluded by a nonlinear regression analysis.

(3)The model indicated a relation how influenced cutting bed height for some variables such as flow rate, drilling fluids properties (rheology), drilling fluids density, cuttings size, drill-pipe eccentricity, and rate of penetration (ROP). The proposed model conclusion is suitable to drilling field case for horizontal slim hole.

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NOMENCLATURE

V =Annular velocity, m/s
D_0 =Wellbore diameter, m
D_i =Drill-pipe diameter, m
d_p =Cutting size, m
C_C =Particle feed concentration
ROP = the rate of penetration, m/h
ρ_s =the cuttings density, Kg/m^3
ρ =the drilling fluid density, Kg/m^3
V_p = cuttings injection rate, Kg/min
E =drill-pipe eccentricity
R_T = cuttings transport ration
n = fluid behavior index and
k =consistency index, $P_a \cdot s^n$.
μ_e = the drilling fluid effective viscosity, $P_a \cdot s$
H =dimensionless cuttings bed height.

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