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Prediction of Cuttings-Induced Annular-Pressure Loss in Extended-Reach Wells

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ABSTRACT

Drill cuttings are broken bits of solid material removed from a borehole drilled by rotary, percussion, or auger methods and brought to the surface in the drilling mud. When these cuttings enter the annulus, they have an effect on the drilling fluid rheology and density, which is, in general, quite difficult to evaluate. By introducing an empirical correlation for the rheological properties of cuttings-laden drilling fluids, this study proposes a pressure-loss prediction method for an extended-reach well (ERW). After verifying the accuracy of this method, a case study is considered and a sensitivity analysis is conducted assuming a yield-power law fluid. The results show that an increased concentration of cuttings in the annulus contributes to an increased annular pressure loss. Compared to their effect on the drilling fluid density, cuttings have a greater impact on the drilling fluid rheology. A larger rate of penetration contributes to an increased annular pressure loss. For higher drilling fluid flow rates, the annular pressure loss first decreases and then it increases. In addition, the annular pressure loss becomes higher as the cuttings' particle size decreases and the cuttings' concentration grows.

KEYWORDS

Pressure loss; cuttings; extended-reach well; yield-power law model; drilling fluid

Nomenclature

a, b, c	Empirical coefficients for the flow behavior index, dimensionless
C_s	Cuttings concentration, %
D_{50}	Average particle size, mm
D_i	Inner diameter of annulus, mm
D_o	Outer diameter of annulus, mm
f_i	Friction factor for each part, dimensionless
F_T	Cuttings transport ratio, dimensionless
K_0	Consistency coefficient of basic drilling fluid, Pa·s^n
K	Consistency coefficient, Pa·s^n
m, p, q	Empirical coefficients for the consistency coefficient, dimensionless
n_0	Flow behavior index of basic drilling fluid, dimensionless
n	Flow behavior index, dimensionless
q_m	Drilling fluid flow rate, m^3/s

v_a	Drilling fluid velocity, m/s
Re	Reynolds number, dimensionless

Greek

γ	Shear rate, s^{-1}
ρ_m	Drilling fluid density, g/cm^3
ρ_s	Cuttings density, g/cm^3
τ_0	Yield stress, Pa
τ	Shear stress, Pa
Δp_a	Total annular pressure loss, MPa
$\sum_{i=1}^{j} \Delta p_{di}$	Pressure loss in deviated sections, MPa
Δp_h	Pressure loss in horizontal section, MPa
Δp_v	Pressure loss in vertical section, MPa

1 Introduction

Extended-reach wells (ERWs) have been widely used in thin productive reservoirs, fractured reservoirs, and low permeability reservoirs. During ERW drilling, the prediction of annular pressure loss is one of the biggest concerns [1]. An inaccurate annular pressure loss may lead to some dangerous drilling consequences such as loss of circulation, wellbore instability, stuck pipe, etc. [2–5].

The reliable prediction of annular pressure loss is dependent on the density and rheology of drilling fluids. On the one hand, after drilling cuttings enter the annulus, the effective density of the annulus drilling fluid will inevitably be affected, thus affecting the bottomhole pressure. On the other hand, drilling fluid rheology is directly related to the calculation of the friction coefficient in the prediction of annular pressure loss. To obtain a reliable pressure loss prediction, therefore, it is important to accurately determine the rheological parameters of cuttings-laden drilling fluids.

Numerous studies on the rheological behavior of drilling fluids have been conducted considering the factors involved such as temperature, pressure, polymer, etc. [4–8]. However, the effect of cuttings on drilling fluid rheology has received little concern, let alone considerations of the cuttings' effect on annular pressure loss. It is commonly assumed that there are no cuttings' effects on the rheological properties of the drilling fluid when calculating the annular pressure loss. In fact, in drilling operations, as shown in Fig. 1 a large amount of drill cuttings enters the wellbore annulus. It is known that cuttings increase the drilling fluid density and result in a higher annular pressure loss, which can reduce the horizontal extended-reach limit [9].

The aim of this study is to couple the cuttings' effects on the rheology and density of drilling fluids into the pressure loss calculation. To evaluate the extent and regularity of the cuttings' effect on the pressure loss, a case study was conducted. The sensitivity analyses of rate of penetration (ROP), drilling fluid flow rate, and cuttings particle size effects on the annular pressure loss were carried out.

2 Methodology

2.1 Rheological Model of Cuttings-Laden Drilling Fluid

For a long time, the rheology of cuttings-laden drilling fluid could hardly be measured. As shown in Fig. 2, due to a too small measuring gap of the rotational viscometer, the solid cuttings cannot enter or would be stuck in the gap. Previous research shows that with the increased amount of cuttings and decreased particle size, the consistency coefficient increases, while the flow behavior index decreases [10].

To describe the rheological performance of drilling fluids, the Herschel-Bulkley model was used in this study. By introducing cuttings effects on rheology into the expression for the Herschel-Bulkley model, a modified version can be expressed as [11]

$$\tau = \tau_0 + K_0 \left(1 + \frac{mC_s^{\,p}}{D_{50}^{\,q}}\right) \gamma^{\,n_0 \left(1 - \frac{aC_s^{\,b}}{D_{50}^{\,c}}\right)} \tag{1}$$

where n_0 is the flow behavior index of the base drilling fluid (without cuttings), dimensionless; K_0 is the consistency coefficients of the base drilling fluid (without cuttings), Pa·s^n; C_s is the cuttings concentration, %; D_{50} is the median size of cuttings, mm; a, b, c, m, p and q are empirical coefficients.
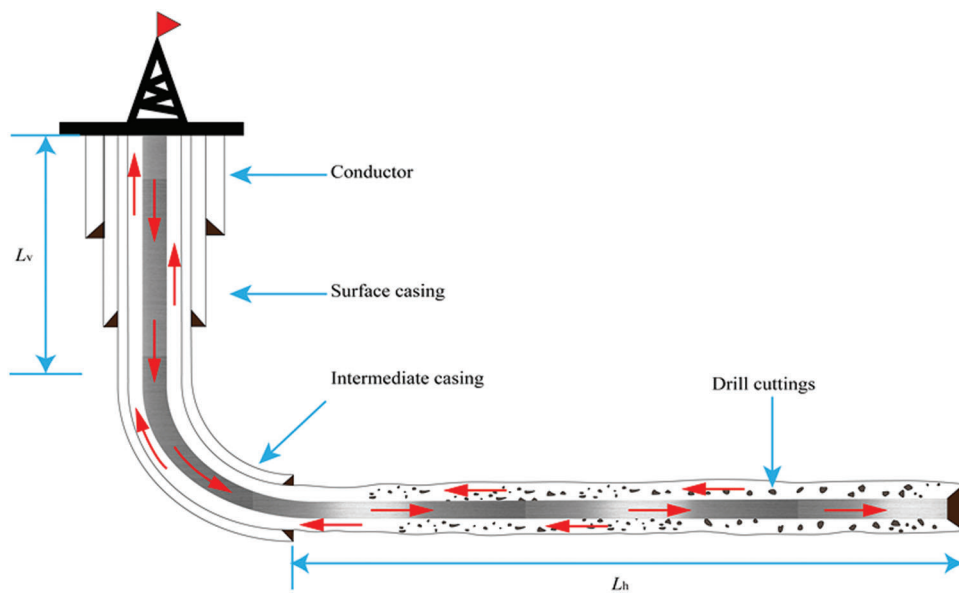

Figure 1: Schematic of an extended-reach well with cuttings in an annulus
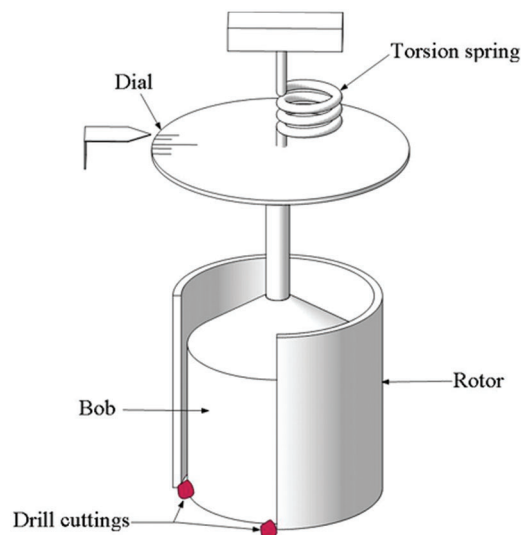
Figure 2: Schematic of a rotational viscometer with cuttings

2.2 Calculation of Cuttings Concentration

Cuttings concentration directly affects the density and rheology of the drilling fluid. Nevertheless, the calculation procedure for the cuttings concentration is complicated due to the iterative calculation involved. Fig. 3 summarizes the process for determining the cuttings concentration.
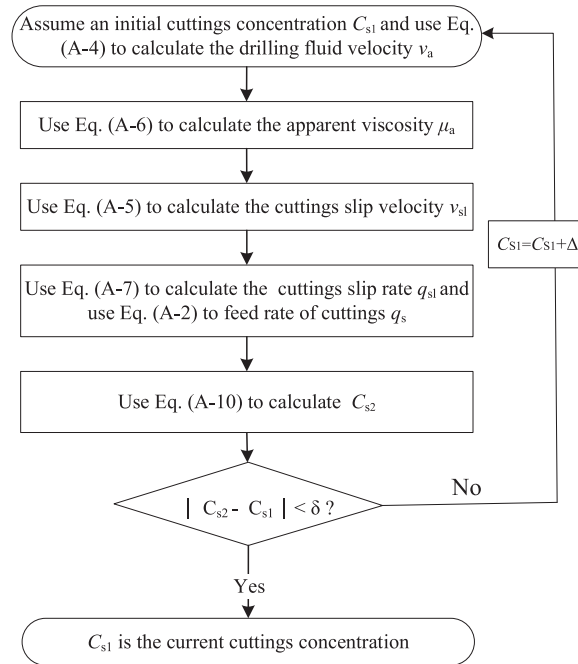
Figure 3: Computational flowchart of cuttings concentration

The volume fraction of drill cuttings in the annulus is defined as [12]

$$C_s = \frac{q_s}{q_s + F_T \times q_m} \tag{2}$$

where q_s is the feed rate of cuttings, m^3/s; q_m is the drilling fluid flow rate, m^3/s; and F_T is the cuttings transport ratio, dimensionless. Please refer to Appendix A for the details of the cuttings concentration calculation.

In the process of drilling, as the cuttings enter the annulus, the material in the wellbore becomes a mixture of drilling fluids and cuttings [12]. The effective density of the mixture can be determined by

$$\rho_e = \rho_m(1 - C_s) + \rho_s C_s \tag{3}$$

where ρ_e represents the effective density of the mixture, g/cm^3; ρ_m represents the fluid density, g/cm^3; ρ_s represents the solid cuttings density, g/cm^3.
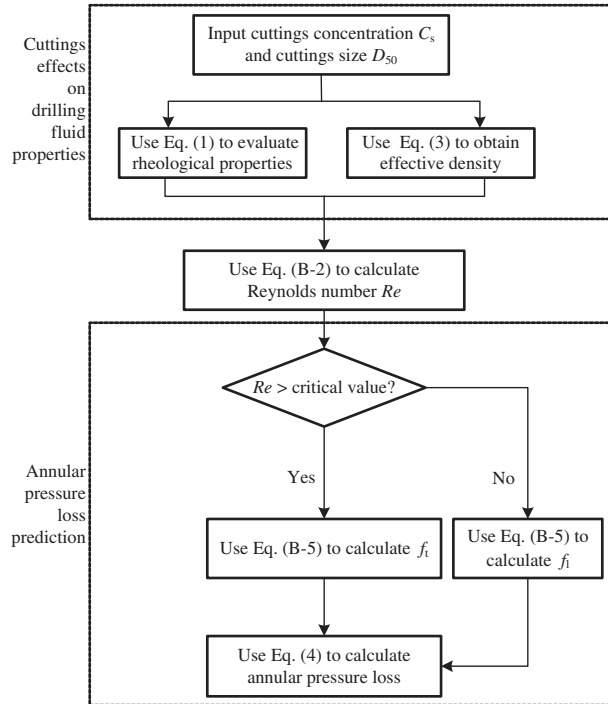
2.3 Prediction of Annular Pressure Loss

A horizontal ERW can be mainly divided into vertical section, deviated sections, and horizontal section. Accordingly, frictional pressure loss Δp_a in an annulus can be calculated by

$$\Delta p_a = \Delta p_v + \sum_{i=1}^{j} \Delta p_{di} + \Delta p_h \tag{4}$$

where Δp_v is the pressure loss in the vertical section, MPa; Δp_{di} is the annular pressure loss in the deviated

section, MPa; Δp_h is the annular pressure loss in the horizontal section, MPa. Please refer to Appendix B for the details of the pressure loss of each section. The calculation process of annular pressure is shown in Fig. 4.

Figure 4: Flowchart of annular pressure loss computation

3 Results and Discussion

Considering the cuttings effects, a horizontal ERW was selected to analyze the effects of different parameters on the annular pressure loss [11]. The input data for the parameter sensitivity analysis is presented in Appendix C.

3.1 Model Validation

The effectiveness of the proposed method is verified by the experimental results in the literature [13]. The experiment was carried out in a flow loop with non-Newtonian fluids. With cuttings injection, the test facility can test the friction annular pressure loss for cuttings-laden drilling fluids. For comparison, the same parameters including consistency coefficient, flow behavior, pipe diameters, and drilling fluid density were used in the proposed method. Fig. 5 shows the pressure loss *vs*. average fluid velocity for a given drilling fluid.

The presented method with cuttings effects follows well the experimental results of Sorgun et al. [14,15]. It is evident that the presented model has a high degree of accuracy to predict the pressure loss.

3.2 Effect of Rate of Penetration

The rate of penetration (ROP) is defined as the speed at which the drill bit breaks the rock. The ROP has an inevitable effect on the concentration of cuttings. Under the same conditions, the cuttings concentration increases with the increase of the ROP, which has a great impact on the drilling fluid density and rheology. Therefore, the ROP has a great impact on the annular pressure loss.
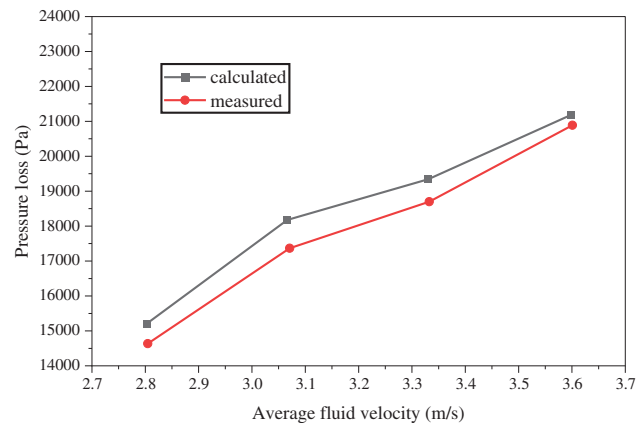
Figure 5: Comparison between the experimental results and the proposed method

For comparison, the annular pressure loss was also calculated for the case that only considered the effect of drill cuttings on the drilling fluid density. The results for annular pressure loss *vs*. ROP are presented in Fig. 6.
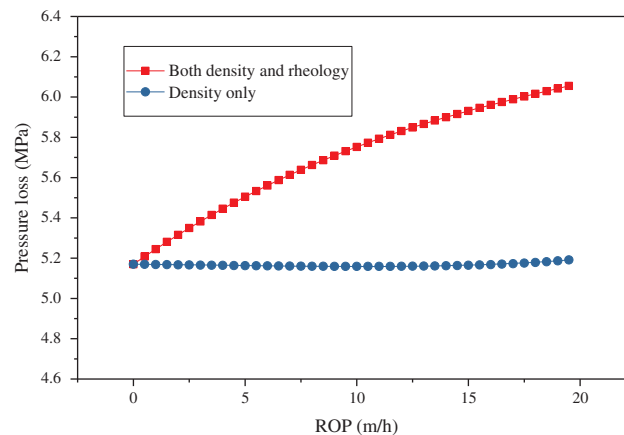
Figure 6: Effects of ROP on annular pressure loss with the effect of cuttings

When only considering the cuttings effects on annulus fluid density, the variation of annular pressure loss is not noticeable. This trend clearly indicates that there is little change in annular pressure loss if only the cuttings effect on drilling fluid density is considered. On the contrary, a significant growth trend can be seen with the cuttings effects on both the density and rheology of the drilling fluid. This can be explained by the fact that a higher ROP results in a higher production of cuttings in an annulus [16]. As a result, the effect on rheology leads to an increase in the annular pressure loss as ROP increases. Considering the effect of cuttings on both the density and rheology of the drilling fluid, Fig. 7 shows the variation in annular pressure loss as the ROP grows for varying flow rates.

The higher the ROP at a given flow rate, the greater the annular pressure loss. The reason for this trend is that the cuttings concentration in the annulus increases with the increase of ROP, which leads to an increase in the density of the drilling fluid and an increase in viscosity, resulting in an increase in the annular pressure loss.
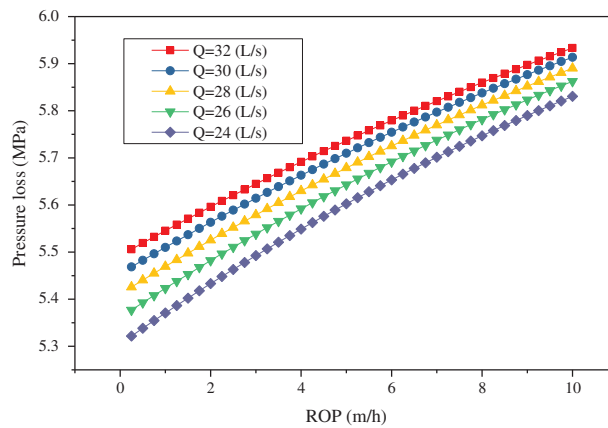
Figure 7: Effects of ROP on annular pressure loss for varying flow rates
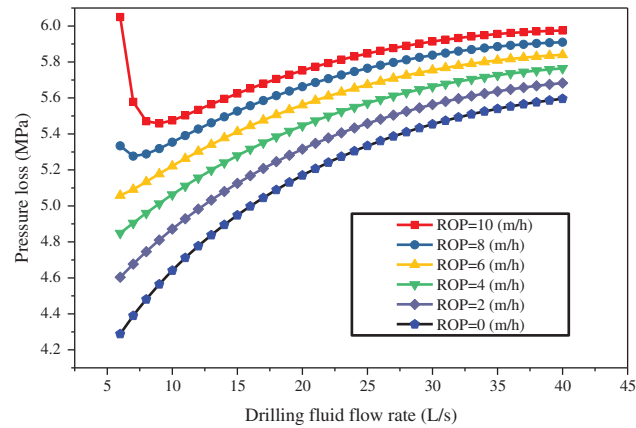
3.3 Effect of Flow Rate

In principle, on the one hand, the increase in flow rate leads to an increase in flow resistance, resulting in a larger pressure loss [17]; on the other hand, the larger the flow rate, the smaller the cuttings concentration, resulting in a reduction in the annular pressure loss.

To illustrate the importance of considering the cuttings effect on the drilling fluid properties, Fig. 8 depicts the comparison of the pressure loss calculated with and without the cuttings effect.
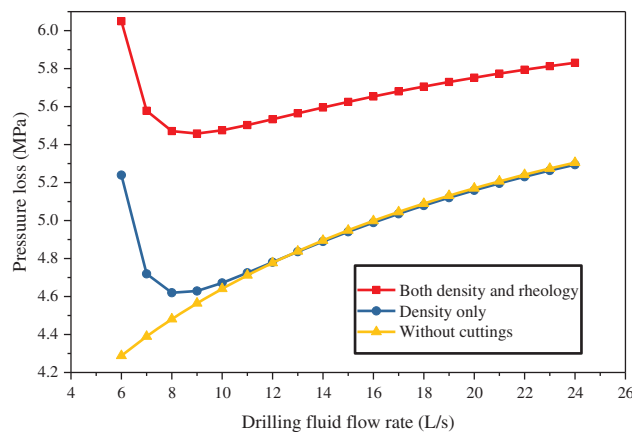
Figure 8: Comparison of pressure loss with and without cuttings effects

If there are no cuttings in the annulus, the pressure loss increases with the increased flow rate. For comparison, when considering the effect of cuttings on drilling fluids, there are two cases for annular pressure loss. The two cases about the pressure loss curves both show a similar trend of decreasing first and then increasing, and the value of the annular pressure loss for each curve is minimized at a certain flow rate (8 L/s in this study). This can be explained by the fact that in the low range of flow rate, the drilling fluid has a weak carrying capacity for cuttings, resulting in a high cuttings concentration and therefore a high annular pressure loss. While, in the high range of flow rate, the increase in pressure loss mainly results from the increase in flow resistance. Furthermore, the annular pressure loss is greater in the case of considering the cuttings effects on the drilling fluid rheology. The variation of annular pressure loss with the drilling fluid flow rate at varying ROPs is shown in Fig. 9.
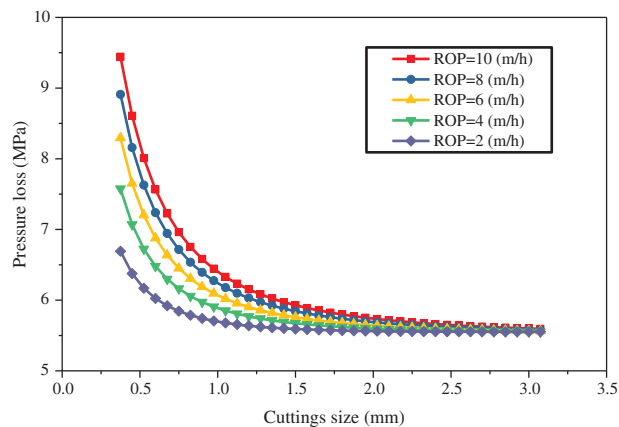
Figure 9: Effects of flow rate on annular pressure loss for varying ROPs

The effect of flow rate on pressure loss is related to the ROP. When the ROP is equal to 0, the pressure loss increases with the flow rate. Before the ROP reaches a certain value (6 m/h in this study), the pressure loss increases with the increased drilling fluid flow rate. When the ROP exceeds the certain value, the annular pressure loss first decreases and then increases with the flow rate. This phenomenon can be explained by the reasoning that less cuttings generated at low ROP can be easily carried out of the wellbore, but when cuttings are increasingly generated at high ROP, transportation of the cuttings becomes more difficult and the annular cuttings concentration increases significantly.

3.4 Effect of Cuttings Size

Cuttings size influences the rheological properties of the drilling fluid, which affects the annular pressure loss. Small-sized cuttings have a greater impact on drilling fluid rheology than large-sized cuttings [18]. For the sake of simplicity, the D_{50} is used to describe the size of the drill cuttings. The relationship between cuttings size and annular pressure loss is shown in Fig. 10.

Figure 10: Effects of cuttings size on annular pressure loss for varying ROPs

From the overall trend, the annular pressure loss decreases with increasing drill cuttings size. Moreover, in the range of a large particle size, the reduction in the annular pressure becomes less pronounced. With an identical ROP, the smaller the cuttings size, the greater the annular pressure loss. This is because the small size of the particles results in a large amount of cuttings particles in the annulus, which in turn increases the

consistency of the drilling fluid, ultimately leading to an increase in the annular pressure loss. In addition, small-sized cuttings particles are more likely to swell and hydrate when exposed to water-based drilling fluids.

4 Limitations of this Study

There are still some limitations in this study which need to be further explored. Firstly, the cuttings effects on the rheological parameters of drilling fluid adopted in this study is based on the empirical correlation in the literature, so it is necessary to investigate the effects of different cuttings on the rheological parameters of different types of drilling fluids in the future. Secondly, this study ignored the influence of temperature and pressure on the properties of the drilling fluid in the calculation of pressure loss. Although there are still some shortcomings in this study, a calculation approach is proposed that considers the cuttings effects on the annulus pressure loss, which has important reference value for the accurate calculation of bottomhole pressure.

5 Conclusions

The effect of cuttings on the pressure loss was evaluated by coupling the cuttings effect on drilling fluid rheology. The main conclusions that can be obtained from this study are as follows:

(1) By introducing the empirical correlations of the rheological parameters and analyzing the pressure effect from cuttings, a pressure loss prediction method was presented for ERW.

(2) Cuttings play a significant role in the annular pressure loss considering cuttings effect both on the density and the rheology of the drilling fluid.

(3) With the drilling fluid flow rate increases, the annular pressure loss increases in the low range of the ROP, while the annular pressure loss first decreases and then increases in the high range of the ROP.

(4) Small-sized cuttings have a greater impact on the annular pressure loss than large-sized cuttings.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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Appendix A. Equations for cuttings concentration

The feed rate of cuttings q_s is calculated as follows:

$$q_s = A_b \times ROP \times (1 - \phi) \tag{A-1}$$

where A_b is the area cut by bit, m^2; ROP is the rate of penetration, m/s; ϕ is the porosity of cuttings, dimensionless.

F_T is the cuttings transport ratio, dimensionless, and is defined by

$$F_T = 1 - \frac{v_{sl}}{v_a} \tag{A-2}$$

where the drilling fluid velocity v_a is given by

$$v_a = \frac{q_m}{A_a(1 - C_s)} \tag{A-3}$$

where A_a is the cross-section area of annulus, m^2.

Due to the extremely complicated flow behavior of the drilling fluid in the wellbore, the cuttings slip velocity v_{sl} is obtained only under idealized conditions. The empirical correlation of the cuttings slip velocity can be expressed by Eq. (A-4) [12].

$$v_{sl} = \frac{0.0075\mu_a}{\rho_m D_{50}} \left[\sqrt{\frac{36800 D_{50}}{\left(\frac{\mu_a}{\rho_m D_{50}}\right)^2} \left(\frac{\rho_s - \rho_m}{\rho_m}\right) + 1} - 1 \right] \tag{A-4}$$

where μ_a, the apparent viscosity, is given by

$$\mu_a = 100K \times \left(\frac{144 v_a}{D_o - D_i}\right)^{(n-1)} \times \left(\frac{2n+1}{n}\right)^n \tag{A-5}$$

The cuttings slip rate, q_{sl}, is defined as

$$q_{sl} = A_a v_{sl} \tag{A-6}$$

then from Eqs. (A-3), (A-4) and (A-7), the cuttings transport ratio is given as

$$F_T = 1 - \frac{q_{sl}(1 - C_s)}{q_m} \tag{A-7}$$

Combining the Eqs. (A-1) and (A-7), the following formula is obtained:

$$q_{sl} \times C_s^2 + (q_s + q_m - q_{sl}) \times C_s - q_s = 0 \tag{A-8}$$

Solving Eq. (A-8), the cuttings concentration is obtained as follows:

$$C_s = \frac{-q_s - q_m + q_{sl} + \sqrt{(q_s + q_m - q_{sl})^2 + 4q_{sl}q_s}}{2q_{sl}} \tag{A-9}$$

Since q_{sl} and C_s are cross linked, a numerical method (trial and error method) is used to obtain the value of C_s.

Appendix B. Equations for pressure loss

Frictional pressure loss for the vertical section and the small inclination section is defined as

$$\Delta p_{\mathrm{v}} = \frac{2f_{\mathrm{v}}L_{\mathrm{v}}\rho_{\mathrm{e}}v_{\mathrm{v}}^{2}}{D_{\mathrm{o}} - D_{\mathrm{i}}} \tag{B-1}$$

where v_{v} is the average annular fluid velocity, m/s; L_{v} is the length of vertical section and small inclination section, m. Annular friction coefficient f_{v} can be referred to the literature [11].

Reynolds number Re is often used to distinguish between laminar flow and turbulent flow in engineering. For the Herschel-Bulkley model fluid, the generalized Reynolds number is estimated in Eq. (B-2).

$$Re = \frac{12^{1-n}\rho_{\mathrm{e}}(D_{\mathrm{o}} - D_{\mathrm{i}})^{n}v_{\mathrm{v}}^{2-n}}{K\left(\dfrac{2n+1}{3n}\right)^{n} + \left(\dfrac{2n+1}{n+1}\right)\left(\dfrac{D_{\mathrm{o}} - D_{\mathrm{i}}}{12v_{\mathrm{a}}}\right)^{n}\tau_{0}} \tag{B-2}$$

where $Re < 2100$ for laminar flow, $Re \geq 2100$ for turbulent flow.

In the deviated section, the cuttings can easily accumulate in the annulus to form a cuttings bed under gravity. It is therefore necessary to add a correction to the annular pressure loss calculation when the cuttings are involved. In addition, the eccentricity of the drill string also has an effect on the annular pressure loss. Therefore, the correction factor considering eccentricity should also be added.

Considering the effects of cuttings bed and drill string eccentricity, a correction factor $R_{\mathrm{d}i}$ can be defined as

$$R_{\mathrm{d}i} = R_{\mathrm{c}}R_{\mathrm{e}} \tag{B-3}$$

where R_{c} is the correction factor for cuttings bed and R_{e} is the correction factor for drill string eccentricity. R_{c} can be obtained from Eq. (B-4) [19].

$$R_{\mathrm{c}} = \frac{0.0260686h_{\mathrm{c}}}{f_{\mathrm{d}}}\left[\frac{v_{\mathrm{d}}^{2}}{0.00981(D_{\mathrm{o}} - D_{\mathrm{i}})\left(\dfrac{\rho_{\mathrm{s}}}{\rho_{\mathrm{m}}} - 1\right)}\right]^{-1.25} + (1 + 0.00581695h_{\mathrm{c}}) \tag{B-4}$$

where ρ_{s} and ρ_{m} are the cuttings density and drilling fluid density, g/cm³.

The friction coefficient f_{d} considering the effects of cuttings can be calculated by Eq. (B-5).

$$f_{\mathrm{d}} = \begin{cases} \dfrac{64}{Re}, Re < 2300 \\ \dfrac{0.316}{Re^{0.25}}, Re \geq 2300 \end{cases} \tag{B-5}$$

The cuttings bed thickness h_{c} is expressed by Eq. (B-6) [20].

$$\begin{aligned} h_{\mathrm{c}} = {}& 90.7609 - 61.90965v_{\mathrm{d}} - 0.35468N - 17.10808\varepsilon - 4.52489v_{\mathrm{d}}^{2} + 0.0001N^{2} + \\ & 5.88684\varepsilon^{2} + 0.16236v_{\mathrm{d}}N + 29.04527v_{\mathrm{d}}\varepsilon N + 0.00034v_{\mathrm{d}}\varepsilon N - \\ & 25.10807(\rho_{\mathrm{m}} - 1) + 1.20133v_{\mathrm{d}}\frac{v_{\mathrm{acj}} - 6}{6} + 2.16505\sqrt[3]{\mu_{\mathrm{AV}}} - 3.3953\sqrt[4]{\mu_{\mathrm{AV}}} \end{aligned} \tag{B-6}$$

where N is the rotation speed of drill pipe, rpm; v_{acj} is the cuttings injection velocity, kg/min; and ε is dimensionless eccentricity, which is calculated by Eq. (B-7) [21].

$$\varepsilon = \frac{2e}{D_{\mathrm{o}} - D_{\mathrm{i}}} \tag{B-7}$$

Annular pressure loss in deviated sections with correction factor is given by [22]

$$\Delta p_{\mathrm{d}i} = \frac{2f_{\mathrm{d}}L_{\mathrm{d}i}\rho_{\mathrm{e}}v_{\mathrm{d}}^2}{D_{\mathrm{o}} - D_{\mathrm{i}}}R_{\mathrm{d}i} \tag{B-8}$$

where $L_{\mathrm{d}i}$ is the length of the ith inclination section, m. f_{d} is frictional factor in the deviated sections, dimensionless.

Similar to the deviated sections, in the horizontal section, the pressure loss Δp_{h} is obtained from Eq. (B-8). R_{h} is referred to in the literature [23,24].

$$\Delta p_{\mathrm{h}} = \frac{2f_{\mathrm{h}}\rho_{\mathrm{e}}v_{\mathrm{h}}^2}{D_{\mathrm{o}} - D_{\mathrm{i}}}R_{\mathrm{h}} \tag{B-9}$$

where R_{h} is the eccentric coefficient for horizontal section, which according to the flow regime, can be estimated as Eqs. (B-10) and (B-11) [24].

$$R_{\mathrm{lam}} = 1 - 0.072\frac{\varepsilon}{n}\left(\frac{D_{\mathrm{o}}}{D_{\mathrm{i}}}\right)^{0.8454} - \frac{3}{2}\varepsilon^2\sqrt{n}\left(\frac{D_{\mathrm{o}}}{D_{\mathrm{i}}}\right)^{0.1852} + 0.96\varepsilon^3\sqrt{n}\left(\frac{D_{\mathrm{o}}}{D_{\mathrm{i}}}\right)^{0.2527} \tag{B-10}$$

$$R_{\mathrm{turb}} = 1 - 0.048\frac{\varepsilon}{n}\left(\frac{D_{\mathrm{o}}}{D_{\mathrm{i}}}\right)^{0.8454} - \frac{2}{3}\varepsilon^2\sqrt{n}\left(\frac{D_{\mathrm{o}}}{D_{\mathrm{i}}}\right)^{0.1852} + 0.285\varepsilon^3\sqrt{n}\left(\frac{D_{\mathrm{o}}}{D_{\mathrm{i}}}\right)^{0.2527} \tag{B-11}$$

Appendix C. Input data for annular pressure loss model with cuttings effects

Based on the presented method for annular pressure loss prediction, a three-stage horizontal well is used as a case to analyze the sensitivity of the parameters [12]. Detailed data are presented in Tables 1 and 2.

Table 1: Input data for modeling

Parameters	Value	Unit
Build-up rate	20.55	°/100 m
Eccentricity	40	mm
Horizontal displacement at the end of deviated sections	280	m
Horizontal displacement at KOP	0	m
Inclination at KOP	0	°
Inclination at target base	90	°
Length of vertical section	1956.3	m
True vertical depth (TVD)	2241	m
Flow behavior index	0.4474	dimensionless
Consistency coefficient	1.7893	Pa·s^n
Cuttings density	2.5	g/cm^3
Drilling fluid density	1.2	g/cm^3
Drill string rotation speed	60	r/min

(Continued)

Table 1 (continued)

Parameters	Value	Unit
Empirical coefficient a in Eq. (1).	0.115	dimensionless
Empirical coefficient b in Eq. (1).	0.411	dimensionless
Empirical coefficient c in Eq. (1).	0.743	dimensionless
Empirical coefficient m in Eq. (1).	0.521	dimensionless
Empirical coefficient p in Eq. (1).	0.817	dimensionless
Empirical coefficient q in Eq. (1).	1.554	dimensionless
Pump flow rate	20	L/s
Rate of penetration	10	m/h

Table 2: Casing program data of the well

Casing structure	Casing depths (m)	Casing outside diameter (mm)	Bit size (mm)
Conductor	30	476.3	558.8
Surface casing	700	339.7	444.5
Intermediate casing	2407	244.5	311.2
Open hole	–	–	215.9