Vol.2, No.12, 1394-1399 (2010)
doi:10.4236/ns.2010.212170

Natural Science

New method of predicting surge pressure apply to horizontal well based on casson flow*

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Received 14 September 2010; revised 20 October 2010; accepted 23 October 2010.

ABSTRACT

In order to predict the surge pressure caused in the horizontal well drilling process, a new simple and applicable method has been established. It is based on the general theory of hydrostatic drilling fluid mechanics, and specifically described the flowing physical model towards surge pressure in horizontal well annulus, taking the effect of string eccentricity on the flowing law of drilling fluid into consideration. According to the constitutive equation of casson-mode under one-dimensional steady flow and the equations of annular flow rate under different drill string working conditions, this paper introduced the flow rate computation models of axial laminar flow in eccentric annulus apply to horizontal well, of which the numerical model was calculated by the program called Mathematica, ultimately, a new model for surge pressure prediction towards each interval in horizontal well was put forward. Application examples indicated that it can solve questions easily and precisely, which presents important meaning of guidance to the safety control while horizontal well drilling.

Keywords: Surge Pressure; Horizontal Well; Eccentric Annulus; Casson-Mode

1. INTRODUCTION

While pipe or casing string pulling and running in the well, the drilling fluid adhesive to the string moves with it and the motion of the string has to get over the viscous force of fluid at the same time, which causes an additional pressure on the borehole face, named Surge Pressure, an important effect factor related to the formation stability [1-3]. Traditional computation model of surge pressure is mostly applicable to vertical well [4,5]. The model of horizontal well has also been studied recently, however, it involves mathematic theory of comparative complexity which leads to the inconvenient computation and low efficiency of application, as a result, the predicting model apply to horizontal well still has more space to develop [6-9].

This paper presents a method of predicting surge pressure applicable to horizontal well based on casson flow, because casson-mode is more precise to describe the rheological behaviour of drilling fluid with high shearing rate inside the pipe or around the bit nozzle [10,11]. This new method conjugates the flow rate computation models of axial laminar flow in eccentric annulus and uses Mathematica software conducting the numerical calculation to simplify the computational procedure, which can also help predict the surge pressure caused in vertical well and directional well.

2. PHYSICAL FLOWING MODEL IN HORIZONTAL WELL BORE

This model neglects the compressibility of the fluid and well bore, it does consider the complexities of the non-Newtonian flow of drilling fluid and choose casson-mode as the rheological behavior of the fluid. It is assumed that the drilling fluid is under isothermal laminar flow in eccentric annulus with fixed-length in the axis, and at the same time it considers the motion parameters of every spatial point in flow field to be time-invariant, which can simplify the calculation with negligible impact on the predicting result. This is because the previous predicting results under the hypothesis of traditional models are a little more conservative, that means the predicting magnitude is bigger than normal, but this prerequisite of steady flow can make an effect of correction [12-15].

In the intervals of deviated hole and horizontal hole, action of gravity makes the string diverge from the borehole central axis, and the annulus between the string and borehole tends to be eccentric, which will influence

*Project of Natural Science Foundation of Heilongjiang Province, China: The Study on Membrane Drilling Fluid Technology

the flowing pattern of the drilling fluid, that means the assumption of concentric annulus generally accepted in drilling annular hydraulics computation will not be applicable any more [16-19].

Figure 1 and **Figure 2** present respectively the physical flowing model in eccentric annulus and the simplified model of flowing section in eccentric annulus. The borehole radius is D_h, the outside radius of running string is d_o, the inside radius of running string is d_i, the hole deviation angle is α, the average annular flowing velocity of drilling fluid is $\overline{v}$, the velocity of running string is v_p, the eccentric arm between the axis of the string and that of the borehole is e, and the clearance, at any circumferential angle θ, between the outside surface of the string and the inside borehole wall is h,

$$h = \sqrt{D_h^2 - e^2 \sin^2\theta} - d_o + e\cos\theta$$

We choose a micro hexahedron unit at any circumferential angle θ in the annulus along the direction paralleled with the flowing. In **Figure 3**, τ is the shear stress between fluid layers, L is the length of fluid along the flowing direction, and Δp is the pressure drop within that length L. In a steady-flow model, because the external forces on the micro unit should balance we can get this [20]:

$$\frac{\partial p}{\partial z} + \frac{\partial \tau}{\partial y} = 0 \qquad (1)$$

When the shape of flowing section along the flowing direction is considered invariable and the fluid is incompressible, we get this:

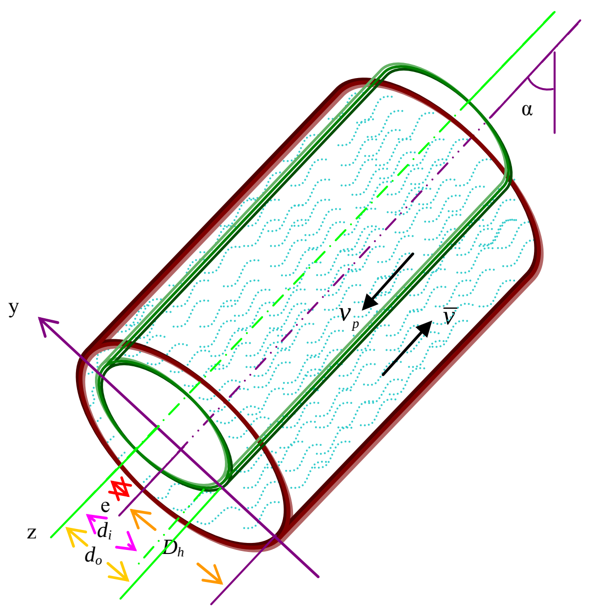

Figure 1. Physical flowing model in eccentric annulus.

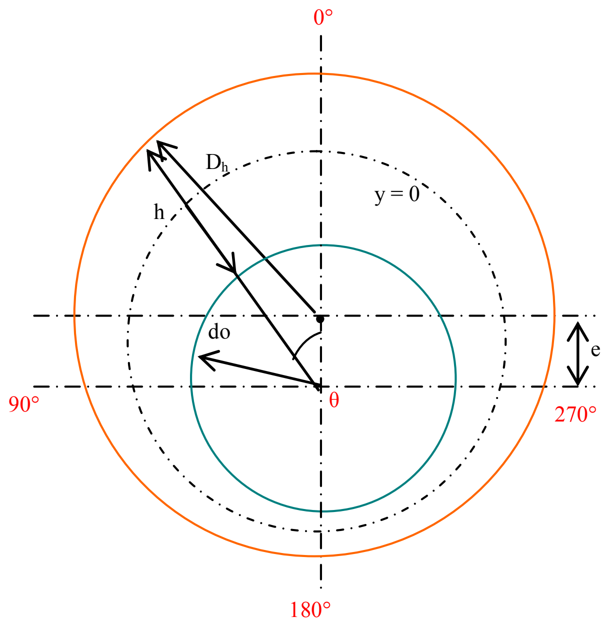

Figure 2. Simplified model of flowing section in eccentric annulus.

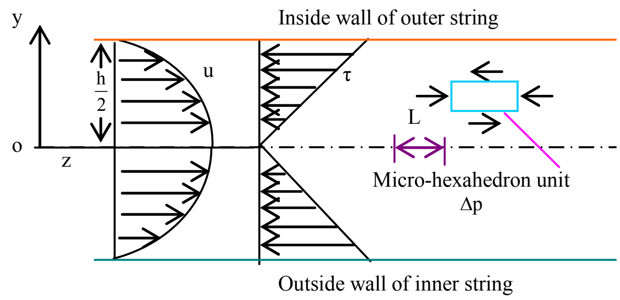

Figure 3. Force analysis of annulus fluid.

$$-\frac{\partial p}{\partial z} = \frac{\Delta p}{L} \qquad (2)$$

So the surge pressure in the borehole annulus at the hole deviation angle α is:

$$P_s = \frac{\Delta p}{L}\cos\alpha \qquad (3)$$

3. COMPUTATIONAL MODEL ESTABLISHING

3.1. Flow Rate Computation in Eccentric Annulus

According to the coordinate system showed in **Figure 3**, casson flow's rheological equation is:

$$\tau = \left[\eta_\infty^{1/2}\left(-\frac{du}{dy}\right)^{1/2} + \tau_c^{1/2}\right]^2 \qquad (4)$$

Combine **Eq.4** with **Eq.1**:

$$\frac{du}{dy} = -\left(\frac{\Delta p}{\eta_\infty L} y + \frac{\tau_c}{\eta_\infty}\right) + \frac{2}{\eta_\infty}\sqrt{\frac{\Delta p \tau_c}{L} y} \quad (5)$$

Integrate the above equation, then the point velocity of fluid at any circumferential angle θ under different values of y is:

$$\begin{aligned} u(\theta, y) &= \frac{\Delta p}{2L\eta_\infty}\left[\left(\frac{h}{2}\right)^2 - y^2\right] + \frac{\tau_c}{\eta_\infty}\left(\frac{h}{2} - y\right) \\ &- \frac{4}{3\eta_\infty}\left(\frac{\Delta p}{L}\right)^{1/2} \tau_c^{1/2}\left[\left(\frac{h}{2}\right)^{3/2} - y^{3/2}\right] \end{aligned} \quad (6)$$

So the axial laminar flow rate model of casson flow in eccentric annulus is:

$$\begin{aligned} Q &= \int_0^{2\pi} dQ = \int_0^{2\pi} v(\theta) ds \\ &= \int_0^{2\pi} (2d_o + h) \int_0^{h/2} u(\theta, y) dy d\theta \end{aligned} \quad (7)$$

3.2. Flow Rate Analysis under Practical Working Conditions

Four types of working conditions are usually applied on site and they are plugging string with pump opened, plugging string with pump closed, opening string with pump opened and opening string with pump closed. There is much in common between the conditions of plugging string with pump opened and opening string with pump opened under which fluids are expelled from mud pump inside the string and then influence the average flowing velocity in the well, therefore, these two conditions can be merged into one [21-23].

We consider that workstring is rigid and drilling fluid is steady-flow, and take into account the annulus flowing velocity changes aroused by the adhesion effect of drilling fluid. According to the relationship between the displacement of drilling fluid expelled by the running string in unit time and the flowrate in annulus, we can establish the equilibrium equation to get the average flowing velocity in annulus under three different working conditions respectively:

1) Plugging string with pump closed:

$$\bar{v} = 1.5\left[\frac{d_o^2}{D_h^2 - d_o^2} + K_c\right]\bar{v}_p \quad (8)$$

2) Opening string with pump closed:

$$\bar{v} = 1.5\left[\frac{d_o^2 - d_i^2}{D_h^2 - d_o^2 + d_i^2} + K_c\right]\bar{v}_p \quad (9)$$

3) Plugging or opening string with pump opened:

$$\bar{v} = 1.5\left[\frac{d_o^2}{D_h^2 - d_o^2} + K_c\right]\bar{v}_p + \frac{Q_p}{\pi\left(D_h^2 - d_o^2\right)} \quad (10)$$

In the equations above: Q_p is the output volume of mud pump, K_c is adhesion coefficient, dimensionless. Refer to the experienced data and theoretical relationship plate of adhesion coefficient and annular ratio(ratio of string diameter) based on power law flow and casson flow, K_c is generally ranged from 0.4 to 0.5, and when the annulus ratio d_0/D_h is more deviated from 1, the magnitude of K_c is more close to 0.4.

According to the average annular velocity $\bar{v}$ under different working conditions and the annular section area s, $s = \pi\left(D_h^2 - d_o^2\right)$, we can work out the annular flowrate Q_t, $Q_t = \bar{v}s$, corresponding to different working conditions:

$$Q_t = 4.71\left[K_c D_h^2 + (1 - K_c) d_o^2\right]\bar{v}_p \quad (11)$$

$$Q_t = 4.71\left[\frac{\left(d_o^2 - d_i^2\right)\left(D_h^2 - d_o^2\right)}{D_h^2 - d_o^2 + d_i^2} + K_c\left(D_h^2 - d_o^2\right)\right]\bar{v}_p \quad (12)$$

$$Q_t = 4.71\left[K_c D_h^2 + (1 - K_c) d_o^2\right] v_p + Q_p \quad (13)$$

3.3. Computation Model of Surge Pressure

After programming on Mathematica software to compute **Eq.7** and containing different value theory and elliptic integral, we finally got the mathematical model to compute the flowrate of axial laminar flow of casson flow in eccentric annulus (**Eq.14**), here we only give the equation under the working condition of plugging string with pump closed as an example, and the other two conditions should be computed in the same way.

$$\begin{aligned} Q &= \frac{\Delta p}{L}\frac{2}{3\eta_\infty}\left[A\pi + B\varsigma + e^2 d_o \varsigma - \frac{8}{3} d_o \xi + \frac{2e}{3}\xi\right] \\ &+ \sqrt{\frac{\Delta p}{L}}\frac{2\sqrt{\tau_c}}{5\eta_\infty}\left[B\pi + C\varsigma + \frac{8}{3}\xi\right] + \frac{\tau_c}{\eta_\infty}\left[B\pi + C\varsigma + \frac{8}{3}\xi\right] \end{aligned} \quad (14)$$

There into:

$$A = \frac{1}{2}\left(D_h^4 - e^3 d_o - d_o^4\right) + D_h^2 e^2 + D_h^{2.64} e^{2.64} d_o^{-2.2}$$

$$B = d_o^3 - D_h^2 d_o - e^3 - D_h^{2.64} e^{2.64} d_o^{-3.03}$$

$$C = D_h^2 - d_o^2 - e^2$$

$$\varsigma = D_h E\left(\frac{e^2}{D_h^2}\right) + \sqrt{D_h^2 - e^2}\, E\left(\frac{e^2}{e^2 - D_h^2}\right)$$

$$\xi = D_h\left(\left(D_h^2 + e^2\right) K\left(\frac{e^2}{D_h^2}\right) + \left(e^2 - D_h^2\right) K\left(\frac{e^2}{D_h^2}\right)\right)$$

K(m) is complete elliptic integral of the first kind and E(m) is complete elliptic integral of the second kind, of which values can be solved by programming on Mathematica software.

Combine the worked out annulus flowrate corresponding to specific working condition (**Eqs.11-13**) with **Eq.14**, so the pressure gradient $\frac{\Delta p}{L}$ can be calculated, then put it into **Eq.3**, and the surge pressure gradient at the hole deviation angle α in the well bore annulus is got.

Until now, based on the above analysis and calculation, we can calculate the surge pressure gradient P_i of each interval in horizontal well, even including the most complicated well structure as showed in **Figure 4**.

The calculation equations of surge pressure for different well intervals and the total surge pressure expression at any well depth in horizontal well are presented as follow.

- Vertical interval, hole deviation angle α is 0°, $P_i = P_s|_{\alpha=0}$
- Deviated interval (angle gaining interval and angle dropping interval), hole deviation angle α changes from α_1 to α_2, $P_i = \int_{\alpha_1}^{\alpha_2} P_s d_\alpha$
- Hold angle interval, hole deviation angle α is invariant, $P_i = P_s$
- Horizontal interval, hole deviation angle α is 90°, $P_i = P_s|_{\alpha=90}$

Thereinto, "*i*" indicates the sequence number of the interval location in horizontal well, P_i is the corresponding annulus surge pressure when the sequence number is *i*, L_i is the corresponding well depth of that specific interval, so the magnitude of surge pressure at any well depth (*i* = *n*) is: $P = \sum_{i=1}^{n} P_i L_i$.

4. SURGE PRESSURE PREDICTION WITH ACTUAL EXAMPLE

There is a certain horizontal well filled with drilling fluid which presents Casson-mode: τ_c = 1.51 (Pa), η_∞ = 15.5 (mPa.s). The Φ 244.48 (mm) casing pipe of which inside diameter is 222.5 (mm) starts to build angle at a vertical depth of 600 (m) and the initial hole deviation angle α_1 = 8°. The Φ127 (mm) drilling pipe of which inside diameter is 82 (mm) runs at the speed of 1 (m/s) and starts to hold angle at a vertical depth of 2204.82 (m), where the hole deviation angle α_2 = 84° and the well depth is 2306.13 (m). Supposed the working condition is plugging string with pump closed, try to calculate the annular surge pressure at the pipe shoe (in the drilling pipe annulus) and determine the corresponding addition mud density.

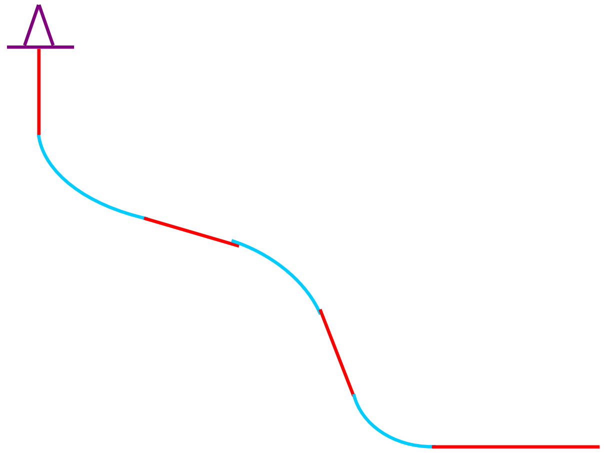

Figure 4. Horizontal wellbore structure.

Some known calculation parameters are mentioned above, they are: τ_c = 1.51 (Pa), η_∞ = 15.5 (mPa.s), $2D_h$ = 222.5 (mm), $2d_o$ = 127 (mm), $2d_i$ = 82 (mm), $\bar{v}_p$ = 1 (m/s), α_1 = 8°, α_2 = 84° and some length parameters: L_1 = 600 (m), L_2 = 2204.82 (m) – 600 (m) = 1604.82 (m). Then we can conduct the calculation as follow.

Firstly, the degree of eccentricity is generally taken as 0.5, so the eccentricity arm *e* = 0.5 * 0.5 * (Φ 244.48 – Φ 127) = 0.0239 (m). Then we substituted D_h {0.11125 (m)}, d_o {0.0635 (m)}, e{0.0239 (m)} into the corresponding expression followed **Eq.14** to get the value of A, B and C in **Eq.14**: A = 0.000110297, B = –0.000937975, C = 0.007979025.

Secondly, using Mathematica program to compute the elliptic integral $E\left(\frac{e^2}{D_h^2}\right)$, $E\left(\frac{e^2}{e^2 - D_h^2}\right)$ and $K\left(\frac{e^2}{D_h^2}\right)$. After substituting and computing we got: E(0.0295) = 1.55914, E(–0.0304) = 1.58267, K(0.0295) = 1.58258, K(–0.0304) = 1.55905, so ς = 0.34691, ξ = 0.00019.

Thirdly, annular ratio {127 (mm)/222.5 (mm) = 0.57} is comparatively small, so we considered the adhesion coefficient Kc = 0.4 and we substituted the numerical values of K_c (0.4), D_h (0.11125), d_o (0.0635), $\bar{v}_p$ (1) in **Eq.9**, then we got the annular flow rate under the condition of plugging string with pump closed: Q_t = 4.71 * (0.4 * 0.11125^2 + 0.6 * 0.0635^2) * 1 = 0.034 (m^3/s).

After calculating the annular flow rate Q_t and parameters such as A, B, C, ς and ξ, we substituted them into **Eq.14**, so we can got the pressure gradient $\frac{\Delta p}{L}$ = 0.1917859 (kPa/m). According to what is presented in **Eq.3**, the annular surge pressure Ps at hole deviation angle α is: Ps = 0.1917859 * cosα.

At vertical interval within the depth of L_1 = 600 (m), its surge pressure:

P1 = $P_1 * L_1 = P_s|_{\alpha=0} * L_1$ = 0.1917859 (kPa/m) * 600

(m) = 115.072 (kPa).

At angle gaining interval within the depth of L_2 = 1604.82 (m), its surge pressure:

P2 = $P_2 * L_2 = \int_{\alpha_1}^{\alpha_2} P_s d_\alpha * L_2$ = 0.1917859 (kPa/m) * $(\sin 84^\circ - \sin 8^\circ)$* 1604.82 (m) = 263.254 (kPa).

The total annular surge pressure value at the pipe shoe is:

P = P1 + P2 = 115.072 (kPa) + 263.254 (kPa) = 378.326 (kPa).

The corresponding addition mud density is:

ρ = P/gH = 378.326 (kPa)/{9.8 (N/kg)*2204.82(m)} = 0.0175 (g/cm^3).

5. CONCLUSIONS

Based on the rheological mode of Casson flow, the flow rate computation models of axial laminar flow in eccentric annulus apply to horizontal well were successfully established. Finally, we developed a new model of predicting surge pressure imposed on different intervals in horizontal well, of which the numerical model could be calculated by the program called Mathematica conveniently. And the magnitude of the predicting surge pressure provided a criterion in determining the addition mud density.

After calculating the actual example using this new model and comparing with traditional predicting method, it is obvious that this new model can be computed easily by the field engineers. Across the steps of derivation of this new model, we concluded that it can calculate flexibly, it provides a method of predicting surge pressures in vertical well and directional well after being simplified. And this new model can also direct the secure production on location through predicting surge pressures under different working conditions of drill string.

6. ACKNOWLEDGEMENTS

We would like to thank the drilling engineers Shurui Zhang and Guobin Li from Daqing Oil Field for their supports to the field test and operations

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