Journal of Natural Gas Science and Engineering 26 (2015) 28–34

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Numerical model for predicting the surge and swab pressures for yield-power-law fluids in an eccentric annulus

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ARTICLE INFO

Article history:
Received 21 April 2015
Received in revised form
27 May 2015
Accepted 1 June 2015
Available online 8 June 2015

Keywords:
YPL fluid
Eccentric annulus
Surge and swab pressure
Narrow-slot approximation technique
Pipe movement

ABSTRACT

Of all of the rheological parameter models for drilling fluids, the yield-power-law (YPL) model is the best one for performing actual calculations. However, no exact general analytical solution has been found for YPL fluids in both concentric and eccentric annuli because currently, all of the published methods for predicting the surge and swab pressures for YPL fluids apply the narrow-slot approximation technique.

To analyze the actual flow characteristics of YPL fluids in an eccentric annulus, this paper introduces an exact model for predicting the surge and swab pressures based on fluid mechanics and the properties of YPL fluids. This model fully analyzes the effects of the rheological parameters of drilling fluids, of the geometric parameters of the annulus and of the pipe velocity on the surge and swab pressures. The results show that the maximum velocity weakens with an increased clearance (θ) when the main flow path is in the range of $\theta = 0 \sim 120$ deg, that the surge and swab pressures decrease with an increase in the eccentricity of the annulus but increase rapidly with an increase in the diameter ratio, and that the surge and swab pressures are most sensitive to changes in the fluid behavior index (n) when $0.7 < n < 1$.

When the results of this model are also used to evaluate the validity of the narrow-slot model, it is found that the accuracy of the narrow-slot model, which is slightly affected by the rheological parameters (τ_0, K and n), is high when the diameter ratio is larger than 0.8 (i.e., the accuracy is within 2% error). However, when the diameter ratio is less than 0.6, the accuracy is influenced by only a few factors, among which Bingham plastic fluids ($n = 1$) has the most effect, followed by power-laws fluid ($\tau_0 = 0$).

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1. Introduction

As a special non-Newtonian fluid, a drilling fluid is characterized by its thixotropy and shear thinning behaviors. The frequently used constitutive equations for the rheological modeling of a drilling fluid are the Bingham plastic (BP) model (Steffe and Daubert, 2006), the power-law (PL) model (Hanks, 1978) and the yield-power-law (YPL) model (Platzer, 1966). However, power-law fluids disregard the yield flow and only manifest the shear thinning behavior of drilling fluids. Bingham plastic fluids and YPL fluids, where the flow is possible only when the shear stress is greater than the yield stress (YS), manifest both thixotropy and shear thinning behaviors. In addition, it is well-known that the rheological properties of a drilling fluid best match the YPL model, of which the BP model (when $n = 1$) and the PL model ($\tau_0 = 0$) are special forms.

Although the YPL model best matches the rheological properties of a drilling fluid, the three-parameter constitutive equation makes it impossible to obtain an analytical solution to predict the surge and swab pressures and is also difficult to apply in the field (Ahmed, 2009).

An analytical model for predicting the surge pressure in an eccentric annulus is based on the laminar flow of Casson fluids was reported (Sun et al., 2010), but the plug zone flow (or rather, the boundary condition $\tau_0 = 0$) was ignored. An exact analytical model to predict the surge and swab pressures for BP fluids in an eccentric annulus was developed (Tang et al., 2014), but it also disregarded the yield stress as a boundary condition. The steady laminar Couette flow of PL fluids and YPL fluids in an eccentric annulus was employed by Yang and Chukwu (Yang and Chukwu, 1995a, 1995b) and Srivastav (Srivastav, 2013) to analyze the problems the surge and swab pressures encountered when tripping inner pipes, and these solutions were presented as a collection of curves and tables.

A finite volume algorithm was developed to investigate the surge and swab pressures for PL and modified YPL fluids in an eccentric annulus when tripping a rotating inner pipe (Hussain and

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http://dx.doi.org/10.1016/j.jngse.2015.06.001
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Sharif, 2000; Hai-qiao and Ji-zhou, 1994). These results showed that the axial-flow rate increased with an increase in the eccentricity and in the rotational speed of the inner pipe under the same axial pressure gradient. Based on the second-order finite-difference scheme, a numerical model was established to predict the surge and swab pressures for YPL fluids in an eccentric annulus (Hussain and Sharif, 1997), and the results were presented as a collection of curves.

This paper presents an exact numerical model to predict the surge and swab pressures of YPL fluids in an eccentric annulus. This model also provides a convenient means for carrying out a systematic parametric study.

2. Modeling

To investigate the surge and swab pressure of YPL fluids in an eccentric annulus, a numerical model was developed based upon the following assumptions: (1) there is a fully developed steady-state laminar flow in the eccentric annulus; (2) the inner pipe is tripping at a constant speed; (3) the flow is isothermal; (4) the fluid constitutive equation obeys the YPL model; (5) the fluid is incompressible; (6) the wall slippage can be ignored; (7) the pipe is close-ended.

The velocity profile of the eccentric annulus flow is shown in Fig. 1; Region II is a plug zone flow area for fluids with YS; when $\tau_0 = 0$, the thickness of Region II is equal to zero (i.e., it is a PL fluid). According to fluid mechanics, the velocity is constant in the plug zone, where$u_2(r,\theta) = const.$

2.1. Governing equations

The axial momentum equation for a fully developed steady-state laminar flow for incompressible fluids in the eccentric annulus with an arbitrary, constant cross-sectional area (Fig. 1) can be written as (Haciislamoglu and Langlinais, 1990):

$$\frac{\Delta P_s}{\Delta L} + \frac{\tau_{rz}}{r} + \frac{\partial \tau_{rz}}{\partial r} = 0 \tag{1}$$

The general solution of Eq. (1) is given by:

$$\tau(r,\theta) = \frac{C}{r(\theta)} - \frac{1}{2}\frac{\Delta P_s}{\Delta L} r(\theta) \tag{2}$$

2.2. Velocity profile

For Region II, by substituting the shear stress boundary conditions, $\tau_{rz1}(r_1(\theta),\theta) = \tau_0$ and $\tau_{rz3}(r_2(\theta),\theta) = -\tau_0$, into Eq. (2), the constants of Eq. (2) for the inner and outer areas of Region II are derived as shown in Eq. (3).

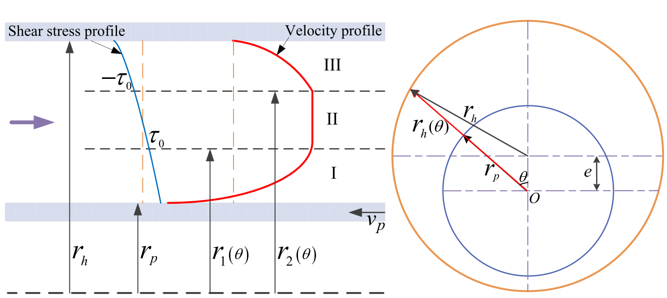

Fig. 1. Velocity profile of the annulus.

$$\begin{cases} C_1 = \tau_0 r_1(\theta) + \dfrac{1}{2}\dfrac{\Delta P_s}{\Delta L} r_1(\theta)^2 & \textit{Region I} \\ C_3 = -\tau_0 r_2(\theta) + \dfrac{1}{2}\dfrac{\Delta P_s}{\Delta L} r_2(\theta)^2 & \textit{Region III} \end{cases} \tag{3}$$

Therefore, the constitutive equations for Regions I and III are given in Eq. (4). By substituting Eq. (4) into Eq. (2) in combination with the boundary conditions of Region I and III; which are $u_1(r_p,\theta) = v_p$ and $u_3(r_h(\theta),\theta) = 0$, respectively; the velocity profiles can be expressed by Eq. (5).

$$\begin{cases} \tau_{rz1} = \tau_0 + K\left(\dfrac{\partial u}{\partial r}\right)^n & (r_p \le r \le r_1(\theta)) \\ \tau_{rz3} = -\tau_0 - K\left(\dfrac{\partial u}{\partial r}\right)^n & (r_2(\theta) \le r \le r_H(\theta)) \end{cases} \tag{4}$$

$$\begin{cases} u_1(r,\theta) = \displaystyle\int_{r_p}^{r} \left(-\frac{\Delta P_s}{2K\Delta L} r - \frac{\tau_0}{K} + \frac{C_1}{Kr}\right)^{\frac{1}{n}} dr + v_p & (r_p \le r \le r_1(\theta)) \\ u_3(r,\theta) = \displaystyle\int_{r}^{r_h(\theta)} \left(\frac{\Delta P_s}{2K\Delta L} r - \frac{\tau_0}{K} - \frac{C_3}{Kr}\right)^{\frac{1}{n}} dr & (r_2(\theta) \le r \le r_h(\theta)) \end{cases} \tag{5}$$

Due to the constant velocity in Region II (i.e., the plug zone), Eq. (6) can be derived as follows:

$$u_2(r,\theta) = u_1(r_1(\theta),\theta) = u_3(r_2(\theta),\theta) \tag{6}$$

2.3. Boundary conditions of Region II

Due to the equilibrium of forces in Region II (i.e., the plug zone), the shear stress of a fluid acting on the plug zone equals the frictional pressure drop by the flow of the plug zone. This equilibrium equation is shown in Eq. (7).

$$\Delta P_s A = \tau_0 (S_1 + S_2) \tag{7}$$

where $A = \pi(r_2^2 - r_1^2)$ and$S_1 + S_2 = \pi \Delta L(r_1 + r_2)$. Therefore, the equation for determining the thickness of the plug zone is given by:

$$\pi_2 = \frac{2\tau_0}{\Delta P_s/\Delta L} \tag{8}$$

According to the geometrical conditions in Fig. 1, the outer boundary condition of the plug zone is given by Eq. (9). By substituting Eqs. (5), (8) and (9) into Eqs. (6) and (10) can be obtained. Therefore, when given rheological parameters, the geometrical conditions and the pressure drop in annulus by the fluid flow, the inner boundary condition of the plug zone can be obtained by using Eq. (10).

$$r_2(\theta) = r_1(\theta) + \pi_2 \tag{9}$$

$$\int_{r_p}^{r_2(\theta)} \left(-\frac{\Delta P_s}{2K\Delta L} r - \frac{\tau_0}{K} + \frac{C_1}{Kr}\right)^{\frac{1}{n}} dr + v_p = \int_{r_2(\theta)}^{r_h(\theta)} \left(\frac{\Delta P_s}{2K\Delta L} r - \frac{\tau_0}{K} - \frac{C_3}{Kr}\right)^{\frac{1}{n}} dr \tag{10}$$

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