Journal of Natural Gas Science and Engineering 28 (2016) 184–192

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

A new simplified surge and swab pressure model for yield-power-law drilling fluids

Shiming He [a], Ruchir Srivastav [b,1], Ming Tang [a,b], Ramadan Ahmed [b,*]

[a] State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, PR China
[b] University of Oklahoma, USA

ARTICLE INFO

Article history:
Received 9 September 2015
Received in revised form
30 October 2015
Accepted 12 November 2015
Available online 1 December 2015

Keywords:
Surge pressure
Concentric annulus
Exact numerical solution
Regression model
Axial pipe movement
Tripping

ABSTRACTS

Surge and swab pressures have been known as common phenomena to cause wellbore pressure control problems such as lost circulation, formation fracture, fluid influx, kicks, and even blowouts. Accurate prediction of these pressures is very important to avoid associated drilling problems. To date, there is no exact analytical model to predict surge pressure developed in concentric annulus with yield-power-law (YPL) fluids. Most of the available models (analytical and regression models) are developed based on narrow-slot approximation of the annular flow. The models provide prediction for diameter ratio ranging from 0.4 to 0.85 with discrepancy of up to 20%. This paper presents a new regression-based surge-pressure model, which makes accurate predictions (maximum error of ±3%) for wide range of diameter ratios (0.4–0.85). To develop the regression model, an exact numerical model was formulated and extensive numerical simulations were performed. The results were analyzed to formulate a simplified regression model that predicts surge and swab pressures conveniently for YPL fluids without requiring iterative calculation procedures. To verify model predictions, laboratory experiments were conducted in small scale setup (50.8 × 33.5 mm annulus). Model predictions demonstrated reasonable agreement with experimental measurements and exact numerical solutions.

1. Introduction

Often well control problems occur during tripping operation. Excessive surge pressure develops due to several factors including extreme tripping speed, highly viscous mud, narrow annulus, and blocked drillstring. Comparing these factors, pipe velocity has the greatest impact on surge pressure. Thus, accurate prediction of surge and swab pressure can guarantee downhole safety during tripping and allow reasonable control of mud rheological properties and tripping speed for hydraulic optimization.

A number of experimental and field studies (Hemphill et al., 1993; Kelessidis et al., 2007) indicated the accuracy of YPL fluid model in describing flow behavior of drilling fluids. Until now, it has not been possible to obtain analytical solution for the equations of motion to calculate surge and swab pressures for YPL fluids. At present, there are two commonly used methods (narrow-slot approximation and regression model) to predict surge and swab pressures for YPL fluids.

Both exact and approximate hydraulic surge pressure models (Chukwu, 1995; Flumerfelt et al., 1969; Fontenot and Clark, 1974; Schuh, 1964) have been developed for power law (PL) fluids. The solutions have been presented in different forms such as regression models or a family of curves. Based on field measurements, (Burkhardt, 1961) developed a semi-empirical surge pressure model for Bingham plastic (BP) fluid. The model predicts surge and swab pressure without applying numerical calculation procedures.

Very limited studies have been conducted to model surge pressure for YPL fluids. An earlier study (Osorio and Steffe, 1991) developed a numerical model to predict surge pressure for YPL fluids in concentric annulus with axial motion of the inner pipe. A similar model (Haige and Xisheng, 1996) was developed for Robertson-Stiff fluid in concentric annulus and numerical solution were presented as a family of curves and tables.

Recently, experimental and modeling studies (Crespo, 2011; Srivastav, 2013) were conducted to investigate surge pressure in concentric and eccentric annulus for closed-ended-pipe. Measurements showed increase in surge pressure with increase in pipe velocity and diameter ratio, and decrease in eccentricity. Based on

* Corresponding author.
E-mail address: r.ahmed@ou.edu (R. Ahmed).
[1] Currently with Superior Energy Services.

http://dx.doi.org/10.1016/j.jngse.2015.11.027
1875-5100/

the narrow-slot approximation technique, analytical models were developed to calculate surge and swab pressure for YPL fluids in concentric and eccentric annulus (Crespo et al., 2010; Srivastav, 2013), the models showed satisfactory agreement with measurements for test fluids with low consistency index (K). Discrepancies were within 10% error margin when diameter ratio is between 0.5 and 0.79, and pipe velocity is ranging from 0.03 to 0.09 m/s. Both measurements and model predictions confirm that the trip speed (v_p), fluid rheology, diameter ratios (annular clearance) and inner pipe eccentricity significantly affect the surge pressure. This paper present an exact numerical model to predict surge and swab pressure in concentric annulus for YPL fluids, and a new regression model, which has been developed based on exact numerical solutions.

2. Exact numerical model

2.1. Model formulations

An exact numerical model (ENS) has been developed to predict surge and swab pressure for YPL fluids in concentric annulus based on analytical solution of equations of motion of axially moving concentric pipe. The following assumptions are made to develop the model: (i) incompressible fluid; (ii) steady laminar and isothermal flow; (iii) inner pipe tripping with constant velocity; (iv) wall slippage effects are negligible; and (v) the wellbore is perfectly cylindrical. Fig. 1 shows schematic of annular velocity profile of YPL fluids. To develop the analytical model, the flow is divided into three flow regions (Region I, Region II and Region III). Region II is plug zone with thickness π_2. Applying force balance, the thickness of Region II can be expressed as (Fridtjov, 2014):$\pi_2 = 2\tau_0/(\Delta P_s/\Delta L)$. From the geometric relationship (Fig. 1), we get:

$$r_2 = r_1 + \pi_2 \tag{1}$$

where r_1 and r_2 are radial distances of plug region boundaries from the pipe center as shown in Fig. 1 π_2 is thickness of the plug zone. τ_0 is fluid yield stress. $\Delta P_s/\Delta L$ is steady state surge/swab pressure gradient. The momentum equation (White, 2010) for steady annular flow of YPL fluid can be expressed as:

$$\frac{\Delta P_s}{\Delta L} + \frac{\tau_{rz}}{r} + \frac{\partial \tau_{rz}}{\partial r} = 0 \tag{2}$$

where τ_{rz} is axial shear stress in the annulus and r is radial distance from the pipe center. As we know, the solution of momentum equation provides the shear stress profile. At the plug (Region II) boundaries (i.e. $r = r_1$ and $r = r_2$), the shear stress must be equal to yield stress of the fluid. Hence, $\tau_{rz}(r_1) = \tau_0$ and $\tau_{rz}(r_2) = -\tau_0$. Applying these conditions, the following formula for shear stress distribution in the annulus can be developed:

$$\tau_{rz}(r) = \frac{1}{2}\frac{\Delta P_s}{\Delta L}\left(\frac{r_1 r_2}{r} - r\right) \tag{3}$$

The shear stress distributions in Regions I and III are related to the shear rates using the constitutive equations as:

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

where K and n are fluid consistency and behavior indexes, respectively. τ_{rz1} and τ_{rz3} are shear stress distributions in Regions I and III. r_p and r_h are radii of the pipe and hole, respectively. By substituting Eq. (4) into Eq. (3) and applying the no-slip boundary conditions: $u_1(r_p) = v_p$ and $u_3(r_h) = 0$, the velocity profiles of Regions I and III can be obtained:

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

where v_p is the trip speed. u_1 and u_3 are velocity profiles in Regions I and III, respectively. The velocity (u_2) is uniform in the plug zone (Region II). Thus, $u_2(r) = u_1(r_1) = u_3(r_2)$, yielding the following integral relationship:

$$\int_{r_p}^{r_1}\left(\frac{1}{2K}\frac{\Delta P_s}{\Delta L}\left(\frac{r_1 r_2}{r} - r\right) - \frac{\tau_0}{K}\right)^{\frac{1}{n}} dr + v_p = \int_{r_2}^{r_h}\left(-\frac{1}{2K}\frac{\Delta P_s}{\Delta L}\left(\frac{r_1 r_2}{r} - r\right) - \frac{\tau_0}{K}\right)^{\frac{1}{n}} dr \tag{6}$$

Flow rate in the annulus is determined by integrating the velocity profiles in the three regions as:

$$Q_{an} = 2\int_0^{\pi}\left[\int_{r_p}^{r_1} u_1(r) r dr + \int_{r_1}^{r_2} u_2(r) r dr + \int_{r_2}^{r_h} u_3(r) r dr\right] d\varphi \tag{7}$$

For a close-ended pipe, the rate of displacement flow caused by inner pipe movement is given by:

$$Q_{total} = \pi r_p^2 v_p \tag{8}$$

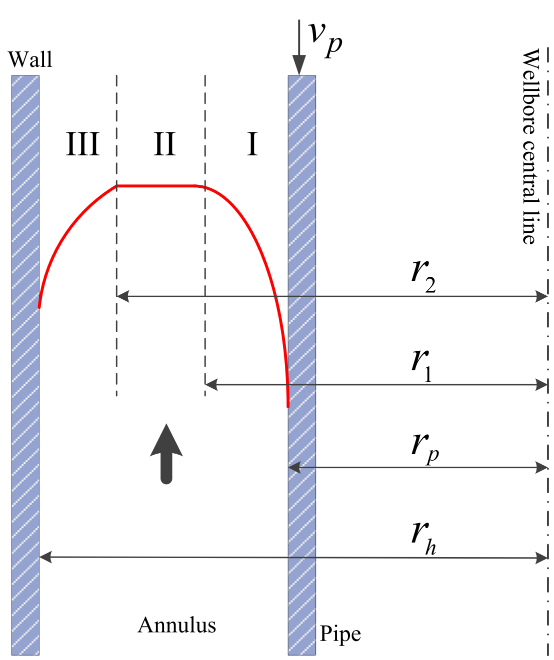

Fig. 1. Profile of velocity for surge pressure in annulus.