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A steady-state approach for evaluation of surge and swab pressures in flows with free surface boundary conditions

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ABSTRACT

A new approach for predicting surge and swab pressures in open-ended pipes running in steady-state is proposed. In addition to the fluid flow through the annulus and drill pipe, the upper ends of drill pipe and annular space are assumed to be opened to the atmosphere, creating two free surfaces. The approach is based on the modified Bernoulli's equation applied to Bingham fluid flows. The pressure differences are not only due to viscous losses but also to fluid velocity differences, and to the fluid column weight differences. The model results are compared with measured data for a Newtonian fluid and the differences lie within an error range of 0% to +10%. A sensitivity analysis is conducted, depicting that the model depends on the Reynolds, Bingham and Froude numbers, and also on the pipe geometry (diameter ratios).

1. Introduction

The upward and downward drill pipe movement is a common operation in well drilling, so that drilling fluid is displaced to the annular space and to inside the drill pipe. Fluid displacement increases (surge) or reduces (swab) the pressure within the wellbore when the pipe is running downwards or upwards, respectively. If the pipe motion is not properly controlled, overpressures may damage rock formation, and fluid circulation can be lost, or underpressures favor fluid invasion to the wellbore leading to a kick or contaminating the drilling fluid. Therefore, predictions of surge and swab pressures can help determine adequate speeds and accelerations for pipe insertion or removal.

Although Cannon (1934) had already identified a higher risk for blow-outs when the drill pipe was withdrawn from the borehole, the first models for predicting surge and swab pressures were only developed in late 1950s and early 1960s (Melrose et al., 1958; Burkhardt, 1961). Since then, a number of studies has been conducted providing either steady-state (Fontenot and Clark, 1974; Bing et al., 1995; Yang and Chukwu, 1995; Rubiandini, 2000; Liu, 2001; Liu and Zhu, 2010; Crespo and Ahmed, 2013) or dynamic models (Lal, 1983; Mitchell, 1988; Wagner et al., 1993; Bing and Kaiji, 1996; Wang and Chukwu, 1996, 1997; Samuel et al., 2003; Mitchell, 2004; Gjerstad et al., 2012).

Steady-state models use momentum and mass conservation equations associated with a constitutive equation for a non-Newtonian drilling fluid so that viscous dissipation is the only effect accounted for the calculation of pressure differences. These models have been applied to investigate not only how fluid rheology and well geometry affect surge and swab pressure drops, but also to find out drill pipe safe trip speeds. For instance, Fontenot and Clark (1974) put forward a model that takes into account variations of drill pipe and annular space cross section and compared the model results with field data for Bingham and Power law fluids. Bing et al. (1995) considered effects of wellbore inclination and pipe eccentricity for Herschel–Bulkley fluids, and Yang and Chukwu (1995) studied the influence of pipe eccentricity for power law fluids. Rubiandini (2000) proposed a new formula to evaluate safe trip velocity and Liu (2001) studied the surge and swab problem for running liners into a well with different pipe end conditions. More recently, Crespo and Ahmed (2013) proposed a simplified surge and swab model for yield power law fluids, and validated their results with laboratory data.

On the other hand, transient models include not only viscous effect, but also the fluid inertia that is affected by the fluid compressibility, leading to more complicated but also more complete approaches (Lal, 1983; Mitchell, 1988, 2004; Wagner et al., 1993; Bing and Kaiji, 1996; Wang and Chukwu, 1996, 1997; Gjerstad et al., 2012). Samuel et al. (2003) and Wagner et al. (1993) have validated the Mitchell's (1988) model by using field data for transient swab/surge response. Recently, Samuel (2010) pointed out the importance of the friction factor and its relation to the axial motion, rotation and vibration of the drilling column in the

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well construction process. In spite of the impressive amount of experimental and rheological studies dealing with more complex aspects of drilling fluids, such as thixotropy and viscoelasticity (Livescu, 2012), most prior works have not included those effects on the modeling of surge and swab. Viscoelasticity and thixotropy can be disregarded if the drilling fluid ages for short periods of time, is completely mixed and is only submitted to high shear rates. Therefore, the fluid can be considered to behave like viscoplastic fluids, such as Bingham or Herschel–Bulkley fluids.

Although the drill pipe is usually open while running the authors of some steady-state studies (Yang and Chukwu, 1995; Liu and Zhu, 2010) considered the pipe to be closed – the flow takes place only in the annulus – as this is the most critical situation for surge and swab pressure predictions. However, some authors (Melrose et al., 1958; Burkhardt, 1961; Fontenot and Clark, 1974) that evaluated steady-state flows through open-ended pipes, as it is a more realistic situation, admitted that the flow is confined within the annular space and pipe walls and that the inside drill pipe pressure drop is counterbalanced by the pressure drop in the annular space. Nevertheless, none of prior works has ever considered free surfaces in the annular space and inside the drill pipe, as shown in Fig. 1. Inside flow velocity and fluid column height may differ from their outside counterpart, leading to different pressure changes in the pipe and in the annular space.

In contrast, the current work presents a steady-state mathematical model to predict surge and swab pressures in open-ended drill pipes taking into account that both drill pipe and annular space are opened to the atmosphere. So far, fluid kinetics and gravitational potential energies are not disregarded and a new correlation for evaluating surge and swab pressures is devised for axial vertical flows of viscoplastic fluids. It is worth of note that this approach is only appropriate for situations where the fluid inside and outside drill pipe is subjected to free boundary condition, as shown in Fig. 1.

As the purpose of the current work is not to deal with all possible complex phenomena involved in the problem, but to show the importance of considering free surface flows when drill pipe and annular spaces are opened to the atmosphere, many assumptions were made to the model so as to reduce the problem complexity considerably. This does not undermine the model, as these effects can be included in more complex and accurate models.

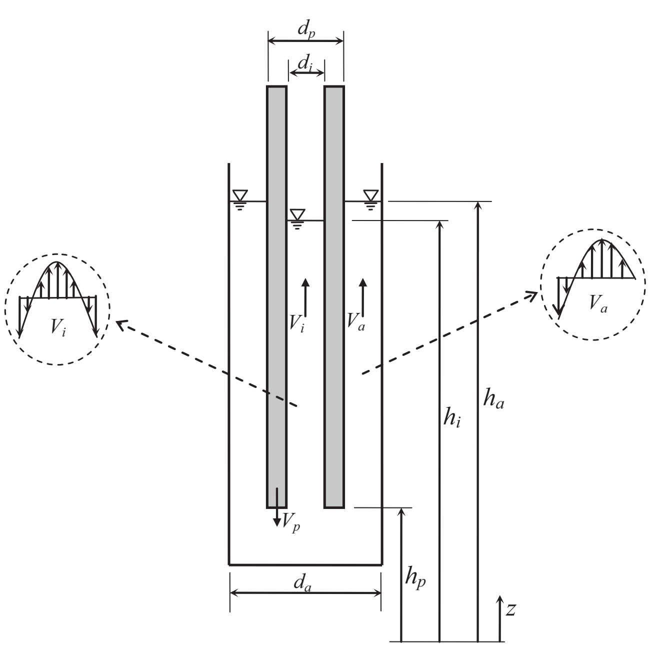

Fig. 1. Geometry of the problem.

2. Mathematical model

Although fluid and pipe accelerations and fluid compressibility play significant roles on the flow start-up, the flow is considered steady and incompressible because transient changes take place in a very short period of time. Additionally, the flow through drill bit nozzles, the annulus and drill pipe cross section variations are all disregarded, as these losses are small in comparison to flow axial losses. As the pipe aspect ratio is significantly large, the flows through the annulus and through the internal pipe are both considered to be laminar, one dimensional and fully developed. Considering the drilling fluid is viscoplastic, its yield stress behavior can be generally represented by the Herschel–Bulkley equation. In order to reduce the number of parameters in the analysis and still keeping the viscoplastic characteristic of the drilling fluid, the Bingham equation that is a particular case of the Herschel–Bulkley model is employed. Nevertheless, the Herschel–Bulkley model can be easily implemented in the current approach, by using the appropriate friction loss correlation.

The problem is thus simplified to two concentric vertical cylinders that respectively represent the drill pipe and the wellbore, in which the space between them is filled with fluid, as shown in Fig. 1. Whilst the external pipe is stationary, the internal pipe moves downward (or upward) with constant speed, V_p, displacing the fluid either to the internal pipe itself or to the annular space. It is also assumed that the height of the internal liquid column, h_i, differs from its annular counterpart, h_a. By applying such assumptions to the flows within the control volumes defined by the fluid-free surface and the pipe end positions, the steady-state momentum balance equation for the annular and inside drill pipe flows can be written respectively as

$$(p_{a1}-p_{a0})A_a-\tau_a S_a(h_a-h_p)-\rho g A_a(h_a-h_p)=0 \tag{1}$$

$$(p_{i1}-p_{i0})A_i-\tau_i S_i(h_i-h_p)-\rho g A_i(h_i-h_p)=0 \tag{2}$$

where p is the pressure, A is the cross-sectional area, τ is the shear stress at the walls, S is the perimeter, h is the height, ρ is the fluid density, g is gravity acceleration and the subscripts, a, i and p are, respectively, annular space, inside pipe and pipe. The subscripts 1 and 0 indicate the positions at the pipe end and at the free surface, respectively. As depicted in Fig. 1, (h_a-h_p) and (h_i-h_p) are, respectively, the inside and outside drill pipe wetted lengths which define the internal and external control volumes. Besides, the upward direction is taken as positive, according to the z coordinate shown in Fig. 1.

Dividing Eqs. (1) and (2) by the respective cross-sectional areas and subtracting the second equation from the first, the following is obtained:

$$(p_{a1}-p_{i1})+(p_{a0}-p_{i0})-\tau_a\frac{S_a}{A_a}(h_a-h_p)+\tau_i\frac{S_i}{A_i}(h_i-h_p)-\rho g(h_a-h_i)=0 \tag{3}$$

As noted, p_{a0} and p_{i0} are both atmospheric pressure values. By applying the Bernoulli equation between the points a_1 and i_1, and neglecting any loss between these points, the following is found:

$$(p_{a1}-p_{i1})=\rho\frac{V_a^2-V_i^2}{2} \tag{4}$$

This dynamic pressure change is only due to internal-to-external pipe diameter variation. For a fully developed Poiseuille–Couette flow, the shear stress at the walls for Bingham fluids is balanced by the pressure force at any cross section of either the annulus