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Modeling and simulation of under-balanced drilling operation using two-fluid model of two-phase flow

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ABSTRACT

Modeling and simulation of gas–liquid two-phase flow in under-balanced drilling (UBD) operation is very important in order to accurately predict the bottom-hole pressure (BHP) and other parameters of two-phase flow. In this paper one-dimensional form of steady-state two-fluid model in the Eulerian frame of reference is used to simulate the two-phase flow in the UBD operation. Simulation is performed to calculate the parameters such as pressure, volume fraction and velocities of two phases at different flow regimes, namely bubbly, slug and churn turbulent flow. The governing equations along with appropriate constitutive relations form a system of coupled ordinary differential equations (ODEs) which are solved using the well-known iterative Newton method. The effect of gas and liquid injection flow rates and also the choke pressure on the wellbore pressures, particularly on the BHP are investigated numerically. In order to validate the results of the current two-fluid model, they are compared with the actual field data and also with the results of the WELLFLO software using different mechanistic models. The comparisons show that the two-fluid model can accurately predict the BHP and other two-phase flow parameters.

Keywords: Under-balanced drilling; Two-phase flow; Two-fluid model; Bottom-hole pressure; Drilling simulation; Aerated mud

1. Introduction

Drilling with two-phase fluid or aerated liquid is used where it is required to keep the BHP lower than the formation pressure. In such situations a gas like nitrogen along with the drilling liquid are injected in the well to keep the mud pressure lower than the formation pressure. This type of drilling is known as under-balanced drilling (UBD) because the two-phase flow pressure at the bottom-hole is lower than the formation pressure. Controlling the flow pressure at the bottom-hole is the key parameter in the success of the UBD operation. If the BHP becomes greater than the formation pressure, the UBD changes to over-balanced drilling (OBD) and if the BHP becomes too lower than the formation pressure this may lead to kicking of the well or may cause collapse of the wall in the well. Therefore, the bottom-hole pressure should be kept in a specific pressure limits known as pressure window. In the UBD, keeping BHP in the window limits is more difficult than the over-balanced drilling because in this method a specific ratio of two fluids (gas and liquid) should be continuously injected in the well to reach the desired BHP which depends mainly on the formation pressure and the choke pressure. Usually, aerated mud is a mixture of nitrogen and gasoil which is used as the drilling fluid. This mixture is injected into the drill-string and after passing through the bit, it comes back to the top of the well through the annulus.

Steady-state behavior of two-phase flow in the UBD operation has been simulated in the several papers. Usually, the authors have employed either correlations or mechanistic models to reach good accuracy in the BHP prediction. Hasan and Kabir (1992) developed a mechanistic model to estimate the gas volume fraction during upward two-phase flow in the

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annulus of a drilling well. Hasan (1995) developed a mechanistic model to estimate the gas volume fraction for downward two-phase flow in the pipes. Lage and Time (2000, 2002) proposed a new mechanistic model for upward two-phase flow in concentric annuli considering different flow regimes including dispersed bubbly, bubbly, slug and churn turbulent flow. They have validated the results using the data of a full scale experimental well. The results show a good agreement between model predictions and experimental data. Guo et al. (1996) calculated the optimal airflow rate in the UBD operation in order to increase the rate of penetration. They used the first law of thermodynamics and closure models for the mixture of mud and air and estimated the BHP and standpipe pressure by trial and error. In their research, an average velocity was used for the mixture; therefore, velocity difference between two phases was neglected. Perez-Tellez (2003) and Perez-Tellez et al. (2003) proposed a mechanistic model to predict the pressure inside the drill pipe and the annular space especially for the BHP in the steady state conditions. Their model predicted parameters of two-phase flow for different flow regimes. Furthermore, the author proposed an iterative algorithm for numerical simulation of unsteady two-phase flow in the vertical annuli in the UBD operation. The proposed model was based on the drift flux model which was coupled by a set of mechanistic models. The comparison of the results shows that these models are in good agreements with the field data for both steady and transient conditions.

Study of the literature shows that most of the previous researches on the prediction of two-phase flow variables in the UBD operation were based on either correlations or mechanistic models. These models may predict the BHP with a good accuracy. However, both of them cannot shed sufficient physical insights into the problem because they are usually based on the experimental data and their validation depends on the conditions they were obtained. Therefore, it seems that one should use better two-phase flow models such as two-fluid model in which a set of partial differential equations are used to describe the physics of the flow.

To the authors' best knowledge, this research is the first study in which the two-fluid model (TFM) of two-phase flow is used to simulate flow behavior in the UBD operation. To this end, the rest of paper is organized as follows. In Section 2 the governing equations of the two-fluid model and corresponding relations are presented. In Section 3 the numerical method and solution algorithm is introduced. The simulation is performed for several drilling wells in Section 4. Finally the conclusions are presented in Section 5.

2. Governing equations of the TFM

In this TFM two phases are considered as the two interpenetrating continua. TFM has a high potential for the analysis of two-phase flows and has extensively been used in modeling different two-phase flow. Governing equations of the TFM were presented in the several papers such as Saurel and Abgral, 1999 and Ambroso et al. (2012). The basis of the two-fluid model is the formulation of two sets of conservation equations for the balance of mass, momentum and energy for each of the phases where the phasic interactions are considered via the interface terms. Since in the UBD operation, the diameter of the pipe is very small compared to its length therefore, the flow can be considered one-dimensional. In the UBD operation, the temperature along the well is usually known, and may be assumed to follow geothermal gradient. Furthermore, the gas phase is assumed to be compressible while the liquid is considered incompressible. Considering these assumptions, the governing equations of the two-phase flow in the UBD operation consist of a continuity and momentum equation for each phase. The mass conservation for the phases along the pipe can be written as in Eqs. (1) and (2):

$$\frac{d}{dx}(\alpha_g \rho_g u_g A) = 0 \tag{1}$$

$$\frac{d}{dx}(\alpha_l \rho_l u_l A) = 0 \tag{2}$$

The momentum equations for the phases can be written as follows:

$$\frac{d}{dx}(\alpha_g \rho_g u_g u_g A) = -A \cdot \alpha_g \cdot \frac{dP}{dx} - \Delta p_{Ig} \frac{d(A\alpha_g)}{dx} + AM_{gw} + AM_{Ig} + A\alpha_g \rho_g g \tag{3}$$

$$\frac{d}{dx}(\alpha_l \rho_l u_l u_l A) = -A \cdot \alpha_l \cdot \frac{dP}{dx} - \Delta p_{Il} \frac{d(A\alpha_l)}{dx} + AM_{lw} + AM_{Il} + A\alpha_l \rho_l g \tag{4}$$

In the above-mentioned equations, the subscripts g, l, and I refer to the gas and liquid phases, and the interface, respectively. Where, α, ρ, u, p and A are the void fraction, density, velocity, pressure and the cross sectional area, respectively. Δp_{Ik} represents the pressure correction term which is the difference between the phasic pressure (pressure inside a pure phase) and the phase pressure at the interface; M_{kw} and M_{Ik} are the wall and interfacial shear force. There are six unknowns in the above equations; therefore, in addition to the conservation equations two additional equations are required to close the system. The first one is an algebraic constraint that expresses the fact that the sum of the volume fractions of the two phases must be one (Eq. (5)), and the next is the equation of state for the gas phase (Eq. (6)).

$$\alpha_l + \alpha_g = 1 \tag{5}$$

$$\rho_g = \rho_g(P_g, T_g) = \frac{M_g \cdot P}{8314 \cdot Z \cdot T} \tag{6}$$

where in Eq. (6), Z is compressibility factor of the gas which can be computed using the Dranchuk and Abu-Kassem (1975) formula as appeared in Eq. (7):

$$Z = \left(0.3265 - \frac{1.0700}{T_{pr}} - \frac{0.5339}{T_{pr}^3} + \frac{0.01569}{T_{pr}^4} - \frac{0.05165}{T_{pr}^5}\right)\rho_r + \left(0.5475 - \frac{0.7361}{T_{pr}} + \frac{0.1844}{T_{pr}^3}\right)\rho_r^2 - 0.1056\left(-\frac{0.7361}{T_{pr}} + \frac{0.1844}{T_{pr}^3}\right)\rho_r^5 + 0.6134(1.0 + 0.7210\rho_r^2)\frac{\rho_r^2}{T_{pr}^3}\exp(-0.7210\rho_r^2) + 1.0 \tag{7}$$

where

$$\rho_r = \frac{0.27P_{pr}}{ZT_{pr}} \tag{8}$$