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Analysis of gas migration in Sustained-Casing-Pressure annulus by employing improved numerical model

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ABSTRACT

Currently, the analysis of Sustained-Casing-Pressure (SCP) tests is limited because some researchers' simulations did not take the effect of gas migration in mud into account and their models were based on Newtonian fluids. This is not consistent with the actual field situations that gas migrates in non-Newtonian fluids. In addition, the yield stress effect was also not taken into account. To ensure the operators a realistic and accurate diagnostic testing for the SCP problem, the improvements of mathematical models in SCP problem are of great significance. In this study, by considering the correlation between gas velocity and drag coefficient, a new formula of gas migration velocity in stagnant non-Newtonian fluids was established. Moreover, the yield stress effect was incorporated in the new model. The validations of field data demonstrate that the new model has the credence to the field work. Furthermore, in this study, the effect of gas migration on SCP problem was paid attention seriously based on new model. To demonstrate the importance of gas migration effect, the analysis of variance (ANOVA) were employed to find out the values of mud properties (flow behavior index, yield stress, length of mud, consistency index) that can most significantly influence the wellhead pressure. Then these most influential parameters were utilized in both the new model (with gas migration effect) and the previous model (without gas migration effect) to conduct the comparison. The comparison result indicate that the value of mud compressibility and the value of cement permeability got by the new model are higher than those by the previous model, and the value of initial gas chamber size got by the new model is lower than that by the previous model. These stress explicitly the necessity and significance of considering gas migration effect and considering the non-Newtonian effect on SCP problem, which should not be neglected. The developed models in this research offer significant insights into the SCP problem, which turns out to be powerful in the application of analyzing the SCP problem. This work can lay the theoretical basis to assist operators in diagnostic testing of wells with SCP problem accurately.

1. Introduction

When the pressure increase is caused by invasion fluid and leads to the casing pressure persistently rebuilding after the bleed-down operation, it is termed Sustained Casing Pressure (SCP). Due to the H_2S and other harmful gases rising to the top of the wellbore, SCP problem usually causes the wellhead corrosion and may reduce the integrity of well under the high pressure for a long time (Goodwin and Crook, 1992; Jackson and Murphey, 1993). The SCP problem is mainly resulted from the poor cement job with cracks contained during well completion. The gas from formation may passes through these cracks and seepage to the top of cement. As time goes on, the gas gradually accumulates in the top of the wellbore and finally forms a chamber, and the wellhead pressure continues growing up. Once the high pressure causes the wellhead leaked, the production of well would be seriously affected. Not only for production wells, but CO_2 injection wells also have SCP problem (Zeng et al., 2012; Celia et al., 2011; Crow et al., 2010; Tao and Bryant, 2014; Bachu, 2017).

In the SCP simulation, Xu first developed the mathematical model without considering the time of gas migration in the mud column (Xu and Wojtanowicz, 2001; Xu, 2002), and this model assumed rapid percolation and ignored gas entrainment in the liquid column. However, without considering the gas migration process may lead the incorrect wellhead pressure estimation, and the gas entrainment may significantly affect the average density of mud and average compressibility of mud.

Huerta et al. (2009) applied Xu's first model (2001) by to study CO_2 leakage rates. Huerta assumed the initially wellhead gas chamber

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volume was zero. However, at the start of pressure buildup stage, this may not be an accurate assumption since the free fluid level in annulus is not known. Rocha adapted a model for SCP analysis that was rooted in the transport processes of the system, and presented an analytical solution to Xu, 2002 model for gas migrating up the annulus through the cement sheath and the liquid column (Rocha-Valadez et al., 2014a). In Rocha's model, the pressure exerted by the mud column was treated as constant, because the mud was enclosed in the annulus, and the mass of the mud was constant. However, the only pressure values employed to analyze the SCP test were final pressure from the bleed-down and buildup (Xu and Wojtanowicz, 2001). And because the rapidly rising gas in mud will leave a trail of bubbles suspended in the well by the yield stress of mud (Johnson et al., 1995a,b), the density of mud cannot be calculated in the usual way. Accordingly, the gas trap in mud will affect the final pressure from bleed down and buildup. As the situation of SCP problem is gas migration in stagnant fluids, the gas status occupies a major position in calculation. Therefore, the pressure exerted by the mud column cannot be treated as constant. Nojabaei et al. (2014) explored the questions of significant changes in temperature that occur in the wellbore can lead to changes in density and compressibility throughout the fluid column. Nojabaei was focusing on heat transfer in wellbore, but did not put the gas migration in mud within the scope of consideration.

Then, in 2003, Xu improved her first model by incorporating the gas migration effect (Xu and Wojtanowicz, 2003), and the iterative solution with a constant formation pressure assumption was required in this model. In 2003's model, Xu also discussed the effect of five unknown system parameters (cement permeability, formation pressure, initial gas concentration in liquid column, mud compressibility and size of gas chamber) on final wellhead pressure. This discussion method was also recognized and employed by other authors (Bourgoyne et al., 1999; Wojtanowicz et al., 2001; Zhu et al., 2012a,b, 2017; H. Zhu et al., 2012a; Guo et al., 2017). In Xu and Wojtanowicz (2003)) improved model, the pressure bleed-down and build up was considered separately, and the whole process (bleed-down and build up) in stages was analyzed. Xu employed the drift-flux model to describe the dispersed two-phase flow, whose research method can be better to reduce the difference with actual field wells. Since the five unknown parameters determine the shape of the wellhead pressure curve, the Xu's improved model can find out the parameters that match the curve scientifically. However, the gas slip velocity in Xu's improved model was correlated based on Newtonian fluids (water) studied by Harmathy (1960), which cannot represent the field conditions with non-Newtonian fluids. Furthermore, the gas entrainment in the liquid column effect was still ignored in Xu's improved model. Although Xu considered the gas migration effect in 2003, based on the gas velocity correlation in Xu's model and assumption of no gas entrainment in mud, the influence of gas migration on wellhead pressure may very small, and will leads to the inaccurate SCP test results. In addition, Xu's study just established a new model for the SCP test, but did not stress the significance of gas migration effect.

In SCP problem, the liquid phase (mud) is stagnant. During the process of testing the final pressure by the gas migration in stagnant mud, the properties of the mud dominate the final results. During the simulation of drift flux model, not only the five system parameters affect the final wellhead pressure, the changed mud properties (flow behavior index, yield stress, length of mud, consistency index) also largely determine the results. Different values of mud properties have different effects on the significance of results. Identifying the effect of mud properties on wellhead pressure change is important in diagnostic testing of wells with SCP problem.

In this study, a new model of gas migration in stagnant non-Newtonian fluids by considering the correlation between gas velocity and drag coefficient was established. In addition, the yield stress effect was considered in the new model. The validation with field data indicates that the new model has the credence for applying into the field. The analysis of yield stress effect in this paper illustrates that the yield stress has a significant impact on the wellhead pressure. These conclusions stress explicitly the necessity and significance of new model with considering non-Newtonian effect and yield stress effect in solving SCP problem. Then the comparisons between the model without considering gas migration effect and the model in this paper were conducted. The comparison result shows that there will be a large difference between new model and previous model. This indicates that considering the gas migration effect is of great value for field applications.

2. Model formulation

In diagnostic testing of wells with SCP problem, the drilling mud is static. And bubble rise in the drilling mud is only affected by buoyancy and drag forces. Generally, the terminal velocity of bubble rise in mud can be determined by equating the buoyancy and drag forces, which is suitable for non-Newtonian fluids, as shown in Eq. (1).

$$F_1 = \frac{1}{6}\pi D_b^3(\rho_l - \rho_g)g = F_2 = \frac{1}{8}\pi D_b^2 C_D \rho_l v_t^2 \tag{1}$$

Where F_1 is the buoyancy force of the single bubble, N; F_2 is the resistance to bubble rise, N; D_b is the bubble diameter, ft; and C_D is the drag coefficient, dimensionless. v_t is the terminal velocity for the bubble, ft/s; ρ_g is the gas density, ppg; ρ_l is the mud density, ppg.

When the single rising bubble reaches a terminal velocity in static liquids, the terminal rise velocity of bubble can be written as:

$$v_t = \sqrt{\frac{4D_b g(\rho_l - \rho_g)}{3\rho_l C_D}} \tag{2}$$

The one-dimensional drift-flux model is chosen to simulate the gas migration in static mud of SCP problem. In this process, the finite difference method and a series of computational cells are adopted to figure out conservation equations (Fig. 1). The entire calculation procedure is conducted by iteration. The whole wellbore is divided into plenty of cells and each cell is very small. The size of bubble D_b for one cell thus can be assumed as a constant during rising (Fig. 2). Therefore, the velocity change in one cell can be neglected for the series of computational cells. At this single cell, the bubble can reach a terminal velocity, so this terminal velocity $v_{t,si}$ can be approximated as the average velocity in this cell. Then the bubble terminal velocity is treated as the bubble slip velocity in mud column.

Therefore, the slip velocity of gas rising in static mud incorporating the swarm bubble effect can be written as follows:

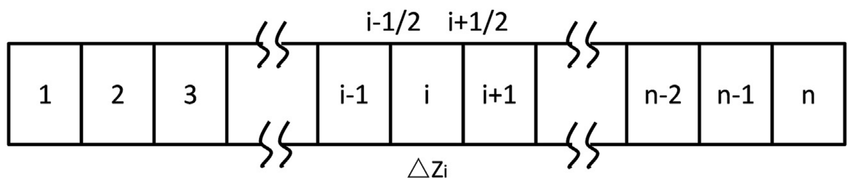

Fig. 1. Computational cells for one-dimensional channel.