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Determination of optimal density difference for improving cement displacement efficiency in deviated wells

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ABSTRACT

In order to explore the optimal relationship between eccentricity and mud-cement density difference in cement displacement process, the flow characteristics for non-Newtonian fluids involved in the laminar displacement inside an eccentric annulus are analyzed with fluid mechanics theory. An optimal density difference criterion is established based on the Herschel–Bulkley fluid model, which can be used to theoretically determine the optimum density difference yielding an optimal cement displacement performance. Numerical simulations are performed with a CFD software to investigate the influence of mud-cement density difference on displacement performance under different eccentricities in highly deviated wells. The results indicate that there is an optimal density difference which can provide the best displacement efficiency at given inclination and eccentricity under laminar flow conditions. The good agreement, between the optimal density differences calculated by the optimal density difference formula and CFD numerical simulations, confirms the validity of the optimal density difference criterion for determining the optimal density difference in highly deviated wells. The research results can provide a practical guide on how to design the cement slurry density and how to install centralizers at highly deviated wells under laminar flow conditions.

1. Introduction

Cement sheath quality is very important for assuring secure and long-term operations of various types of wells in petroleum industry, e.g., production wells, water injection wells, CO_2 injections wells, and CO_2 sequestration wells (Zhang et al., 2010; Beirute and Flumerfelt, 1977). The mud-cement displacing interface plays an important role in affecting the displacement effect. In the cementing process, the cement slurry displaces drill mud in the casing-formation annulus; inclination, eccentricity, and density difference are important factors that affect such displacement efficiency (Mclean et al., 1967; Lockyear et al., 1990; Nelson, 1990; Liu et al., 2001). Moreover, these influencing factors interact with each other, which poses a great challenge for investigating cement displacement process.

Many previous researches have been conducted to quantify the effects of eccentricity and density difference on displacement efficiency based on various rheological models (Vaughn, 1965; Iyoho and Azar, 1981; Crook et al., 1985; Chen et al., 1990; Haciislamoglu and Langlinais, 1990; Tehrani et al., 1992; Zheng, 1995; Zhang et al., 1997; Gao et al., 2005; Sun et al., 2005; Ozbayoglu and Omurlu, 2006; Yang et al., 2008; Deng et al., 2011; Feng et al., 2011). Previous researches have examined the influence of mud-cement density difference and eccentricity on displacement efficiency in highly deviated wells (Savery et al., 2007). It was found that the casing eccentricity affects flow-resistance distribution in the casing-wellbore annulus, and the density difference between cement slurry and drill mud influences the slurry distribution near the interface region due to the gravitational effect (Dutra et al., 2004). These two mechanisms are deciding factors affecting the cementing displacement efficiency (Jakobsen et al., 1991). It is of great importance to build a representative and inclusive model to identify the optimal density difference at certain deviation and eccentricity to improve the cementing quality, in particular, for deviated wells. In this study, we define the optimal density difference as one that can lead to the best displacement efficiency when other factors are held constant.

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The Herschel–Bulkley rheological model (Herschel and Bulkley, 1926) contains three parameters, and can give more reliable descriptions of rheological properties for fluids. It is noted that this more representative model has not been used to determine optimal density difference in previous studies. One of the difficulties for applying the Herschel–Bulkley model lies in that the related flow behavior calculations with the Herschel–Bulkley model tends to be much more complicated (Guo et al., 1997). In this study, on the basis of the Herschel–Bulkley rheological model, the criterion of optimal density difference is first derived for the laminar flow of cement displacing drilling mud in an eccentric annulus. Subsequently, the correctness of the optimal density difference model is verified by comparing the optimal density differences calculated with the derived criterion against the numerical simulation results with the ANSYS FLUENT software (ANSYS, 2011).

2. Laminar flow theory of cement displacement in eccentric annulus

Based on the assumption of the plate flow model, the wellbore annulus can be regarded as plates with varying widths (Liao et al., 2003; Feng et al., 2014). The coordinate system is established between the two plates at a circumferential angle of φ (as shown in Fig. 1): the coordinate origin is at the bottom hole; the axis of annulus center between the casing's outer wall and the borehole is Z-axis pointing to the direction of displacement; and Y-axis points to the direction perpendicular to the wellbore wall.

The following assumptions are made in this study:

- The displacement process is a steady flow. The flow in eccentric annulus is one-dimensional axial laminar flow, which implies that the circumferential velocity is zero;
- There are no mixing and diffusion at the mud-cement interface and no chemical reaction between drill fluids and cementing slurry caused by fluid incompatibility;
- Cement slurry and drill fluid are Herschel–Bulkley fluid, and we do not consider the impact of the flow core; and
- Cement slurry directly displaces the drilling fluid.

According to the above assumptions, the force balance analysis on a finite fluid element in the eccentric annulus is carried out, as shown in Fig. 2.

Based on the hydrodynamic theory, the differential force equilibrium equation for fluid in the eccentric annulus is:

$$\rho\left(\frac{\partial V_z}{\partial t}+V_r\frac{\partial V_z}{\partial r}+V_\varphi\frac{\partial V_z}{r\partial\varphi}+V_z\frac{\partial V_z}{\partial z}\right)=-\frac{\partial p}{\partial z}+\left[\frac{\partial(r\tau_{rz})}{r\partial r}+\frac{\partial\tau_{\varphi z}}{r\partial\varphi}+\frac{\partial\tau_{zz}}{\partial z}\right]-\rho g\cos\theta \tag{1}$$

The shear stress of cement slurry and drill fluid in an eccentric annulus can be described by (Liu et al., 1988; Liao et al., 2003):

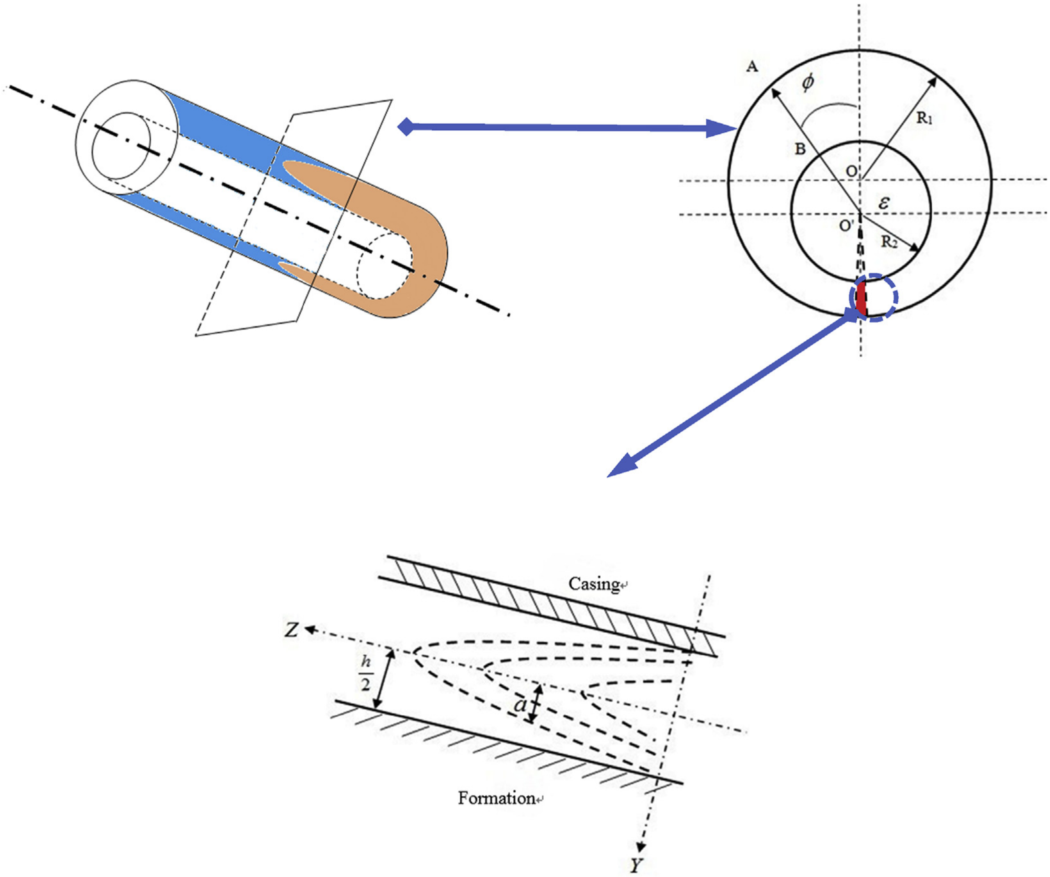

Fig. 1. The schematic diagram of eccentric annulus and the narrower gap in the annulus. The dimensionless eccentricity can be calculated to be: $e=\varepsilon/R_1-R_2$, where e is eccentricity, ε is eccentric distance, R_1 and R_2 are wellbore radius and casing radius.