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Modeling of yield-power-law fluid flow in a partially blocked concentric annulus

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ABSTRACT

Horizontal well is one of the most effective ways of developing unconventional oil and natural gas reservoirs. During horizontal well drilling, a stationary cuttings bed forms on the low-side of the wellbore. Formation of the bed is undesirable and has detrimental effect on wellbore hydraulic and drilling performance. Hydraulic optimization of the process strongly depends on accurate prediction of bed height and frictional pressure loss. Therefore, it is necessary to investigate hydraulic characteristics of horizontal wellbore with cuttings bed, which can be represented by partially blocked concentric annulus when centralizers are used with drillpipe.

In this study, flow in a partially blocked concentric annulus is investigated using Computational Fluid Dynamics (CFD) approach. CFD simulation results are validated using established numerical solutions and experimental measurements obtained from concentric annulus. The analysis is performed for laminar flow of yield-power-law (YPL) fluid. Pressure loss and wall shear stress acting on the cuttings bed are obtained from CFD simulation. Results show significant variation in bed shear stress in the lateral direction. Hence, average bed shear stress ($\overline{\tau}_{bed}$) is used to analyze the result. Unexpected $\overline{\tau}_{bed}$ trend is observed when bed height is increased at constant flow rate. As bed height increases, $\overline{\tau}_{bed}$ slightly decreases at low bed heights until it reaches the inner pipe. For bed height greater than annular clearance, $\overline{\tau}_{bed}$ trend is normal, it increases with bed height.

Existing hole cleaning models require accurate prediction of $\overline{\tau}_{bed}$ and pressure loss in partially blocked concentric annuli. Therefore, combining existing non-circular duct modeling approach and simulation data, simplified models are developed to predict pressure loss and $\overline{\tau}_{bed}$. Model predictions show reasonable agreement with simulation results. Maximum discrepancy of $\pm$10% has been observed.

1. Introduction

Applications of horizontal and directional drilling techniques have been on the rise in recent years because of their unique technology advantages such as improved oil and gas recovery, highly reduced drilling costs and reduced environmental foot print. In spite of widely acceptance of these techniques in drilling unconventional reservoirs, hydraulic optimization and bottom hole pressure management in horizontal and directional drilling are still challenging. Often undesirable cuttings beds form on the low-side of horizontal and inclined wellbores. The formation of cuttings bed has considerable effect on wellbore hydraulics and performance of drilling operation. Bed thickness strongly varies with fluid rheology, annular geometry, annular fluid velocity, flow regime and cuttings size. In addition to increased hydraulic resistance and bottom hole pressure, thick beds cause several drilling problems including: stock-pipe, excessive fluid loss, lost circulation and increased drillstring torque and drag.

Pump rate and fluid rheology are commonly controlled at the surface to optimize drilling process. Pump rate is directly related to annular fluid velocity and shear stress acting on cuttings bed. A number of studies (Ahmed et al., 2001; Chen et al., 2007; Clark and Bickham, 1994; Duan, 2007; Effiong, 2013; Nguyen and Rahman, 1998) documented that increased bed shear stress (Fig. 1) promotes erosion of cuttings bed. Therefore, increasing pump rate is expected to reduce bed height, which in turn reduces hydraulic resistance of the annulus. There is a strong coupling between annular fluid velocity and bed height. As a result, for every flow rate

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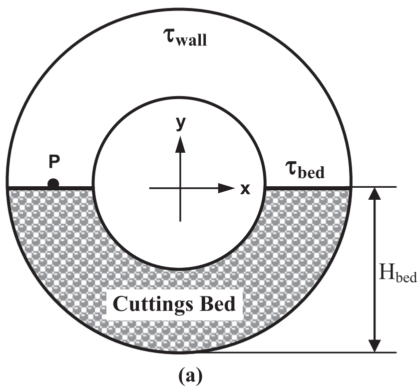

Fig. 1. Cuttings bed formed in concentric annulus: a) horizontal bed profile; and b) actual bed profile.

there is a corresponding bed height (i.e. equilibrium bed height) at which cuttings deposition and removal rates equalize. In addition to bed shear improvement, increased pump rate has strong impact on local fluid velocities close to the bed surface. Increase in local fluid velocity enhances hydrodynamic forces acting on flow protruding bed particles and promotes cuttings transport. Moreover, a substantial increase in fluid velocity can result in turbulent flow condition. Due to formation of eddies and logarithmic fluid velocity profile; turbulent flows are more effective in eroding cuttings beds in horizontal wellbores.

The impact of fluid rheology on cuttings transport is more complicated than that of pump rate. As a constant pump rate, varying fluid rheology can change wall shear stress, fluid velocity profile and flow regime. Increase in viscosity significantly changes flow regime, wall shear stress and local fluid velocity. In horizontal configuration, low viscosity fluids efficiently re-suspend deposited particles; however, they are unable to keep particles in suspension for a long time. As a result, low viscosity fluids transport particles predominantly by rolling on bed surface.

Solid transport mode is different in thick fluids. Local fluid velocity close to flow protruding bed particles is low and insufficient to re-suspend deposited particles. However, thick fluids perform better than low viscosity fluid in keeping particles in suspension for a long time before deposition.

A number of hydraulic models (Ahmed et al., 2001, 2004; Clark and Bickham, 1994; Ford et al., 1996) have been developed to predict equilibrium bed height in horizontal and inclined wells. The models require determination of local fluid velocity at the center of bed particles exposed to the flow field. For laminar flow of YPL fluid ($\tau = \tau_0 + K\dot{\gamma}^n$), the local fluid velocity gradient close to the bed surface can be approximately determined from the average bed shear stress ($\overline{\tau}_{bed}$) as:

$$\frac{du}{dy} = \left(\frac{\overline{\tau}_{bed} - \tau_0}{K}\right)^{1/n} \quad (1)$$

where u is local fluid velocity, y is distance measured from the bed. According Eq. (1), the local fluid velocity at the center of a spherical particle positioned at the bed surface can be estimated as:

$$u = \left(\frac{\overline{\tau}_{bed} - \tau_0}{K}\right)^{1/n} \frac{d_{par}}{2} \quad (2)$$

d_{par} denotes diameter of the particle. Equation (1) is valid when particle diameter is very small compared to hydraulic diameter of the annulus.

In concentric annulus, flow stagnation zones are expected to form at the edges of cuttings bed. As a result, local bed shear stress, τ_{bed}, varies with lateral distance x (Fig. 1). Hence, the maximum bed shear stress is expected to be close to the middle of the bed (Point P). This results in greater bed erosion in the middle section than other parts of the bed, which leads to the formation of slightly curved bed profile (Fig. 1b) with approximately uniform bed shear stress distribution. Therefore, for practical applications, average bed shear stress ($\overline{\tau}_{bed}$) is more relevant than the local bed shear stress ($\overline{\tau}_{bed}$).

This study is focused on investigating laminar flow of YPL fluid in partially blocked concentric annuli (i.e. concentric annuli with cuttings bed). Concentric annular geometry is established in non-vertical wellbores when drillpipe centralizer are used to control hole deviation and minimize the risk of differential sticking. Extensive CFD simulation study has been conducted to examine the effects of fluid properties, annular diameter ratio, and bed height on pressure loss and average bed shear stress.

In the past, a number of wellbore hydraulic studies (Aworunse, 2012; Azouz, 1994; Azouz et al., 1993) were conducted to predict annular pressure loss in a partially blocked annulus. With increasing fluid behavior index (n), annular pressure loss becomes more sensitive to cuttings bed height. Aworunse (2012) developed a simplified model to predict pressure loss in concentric annulus with cuttings bed for power law fluids. However, the model has not been validated. Chen (2005) formulated a semi-empirical model based on effective diameter concepts (Govier and Aziz, 2008; Reed and Pilehvari, 1993; Whittaker, 1985). The model predicts pressure loss of power law (PL) fluid in a partially blocked concentric annulus. Comparison shows reasonable agreement (maximum 25% discrepancy when dimensionless cuttings bed height (h_{bed}) is between 0 and 65%) between model predictions and numerical simulation results for wide range of annular geometries and fluid rheological properties.

Although a number of modeling and experimental studies were conducted on concentric annular flow with cuttings bed, there is no simple and accurate model to predict pressure loss and average bed shear stress. In this study, extensive CFD simulations have been conducted for YPL fluid in concentric annulus varying fluid behavior index, diameter ratio and bed height. Adopting a method developed for non-circular pipes (Kozicki et al., 1966), a simplified model has been formulated to predict pressure loss in a partially blocked concentric annulus for YPL fluid. Model parameters are determined using simulation results.

2. Governing equations and CFD formulation

For isothermal and fully-developed steady-state laminar flow of