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Characterization of drilling fluids filtration through integrated laboratory experiments and CFD modeling

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ABSTRACT

The filtration experiments have always been the focal point for drilling researchers. The physical, chemical, and mechanical behavior of drilling fluid is critical for successful drilling operation. In order to characterize it, permeability plugging test is carried out. But there are certain limitations of this experiment. As the actual field condition cannot be simulated at laboratory scale experiments, there is a need to replicate the same laboratory experiments in numerical models with significant accuracy. After achieving, the desired accuracy of this numerical model, the upscaling of the same numerical model can be used to predict the behavior of drilling fluid with significant accuracy.

The current study uses our past laboratory experiments and a genuine effort has been made to model the permeability plugging test using Fluent package of ANSYS. This paper includes the procedure and results on filtrate and filter-cake characteristics obtained during the laboratory experiments to validate the numerical model. First of all, a comparison between existing numerical models and our current model has been studied to verify the accuracy of our model. Then the model has been extended to characterize the laboratory conditions. Good agreement was observed in comparison of the simulation's results with experimental data.

1. Introduction

With the advancement in numerical simulation, nowadays it has become possible to simulate the complex phenomena like filtration loss in borehole environment. Since, the drilling operation has consistently shifted towards more harsh environment like deep water basins, narrower mud window, and severe wellbore problems such as lost circulation and depleted sand zones; the research in this particular field have attracted attention of whole industry since few decades. With this in mind, the filtrate behavior during drilling operation becomes of immense importance.

Composition of drilling mud especially addition of lost circulation materials (LCM) and lost prevention materials (LPM) dictates the drilling operation in terms of physical, chemical and mechanical behaviors in particular downhole problems and conditions. The solid particles in drilling fluid behave in a certain manner when used for certain type of the formation. This results in either formation of thin and low permeable filter cake or thick or highly permeable filter cake on the borehole wall and consequently it affects the wellbore strength (Aston et al., 2004; Sweatman et al., 2004; Fuh et al., 2007; Salehi et al., 2010, Salehi and Nygaard, 2014).

The efforts have been made to study the effect of drilling mud on different problems. Researchers have shown that the particle size distribution in the drilling fluid plays significant role in wellbore strengthening effect. The main attributing factors are believed to be plugging of fractures by carefully engineered particles and accumulation of annular seal on the borehole wall (Morita et al., 1990; Tran et al., 2010; Salehi and Kiran, 2016). The annular seal on the wellbore termed as mud cake is evaluated on different parameters such as thickness, permeability. It has been also inferred through analytical and experimental models that the low permeability and thin mud cake has positive influence on better wellbore integrity aspect.

In order to characterize this property of drilling fluids, a vast study has been conducted using permeability plugging test in 2000 psi pressure and 250° F temperature. Analytical methods are used to simulate the filtrate and filter-cake behavior. The existing models are very simple and far from the real field conditions. So, there is still a need to explore a more realistic model considering the

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rheological properties of the fluid, particle size distribution in fluid, properties of formation which can give more insight about the wellbore strengthening aspect of drilling fluid. Bearing these limitations in mind, a numerical model has been created to simulate the laboratory conditions for permeability plugging test which can capture the filter cake properties and filtrate behavior. After achieving the results within significant accuracy, this model can be extended to field conditions. The current model is generated using a computational fluid dynamic package FLUENT, which is based on finite volume approach.

The numerical techniques for fluid modeling for filtration process was studied in the past by few researchers (Nassehi, 1998; Pak et al., 2008; Kabir et al., 2011), in which both concepts of fluid flow and mass transfer was considered. Computational Fluid Dynamics has become an efficient method to simulate the liquid–solid two phase flows. These models are based on two models: (a) Eulerian-Lagrangian model and (b) Eulerian–Eulerian model. The first model considers the Eulerian approach for fluid density and flow while the Lagrangian approach is used for modeling each individual solid particle position and velocity. It is used to describe the fluid-solid, solid–solid and solid–wall interaction. But in the permeability plugging test, the amount of solid is far less than the actual borehole conditions.

As per the second model, liquid and solid particles are treated as continuous and inter-penetrating phases as if it is two-fluid phase. In this both liquid and solid particles are treated with separate conservation equations with appropriate interaction conditions, like the viscosity of the total drilling fluid. The Eulerian–Eulerian model is based on kinetic theory of granular flow; the viscosity is regarded as constant and universally accepted for characterization of the particle deposition scheme. Hence, in our study we have adopted the Eulerian–Eulerian Model. This hydrodynamic model adopts the principle of conservation of mass momentum and energy. The continuity and momentum balance equations are given below (FLUENT Inc, 2006):

Continuity Equations.

For Liquid phase:

$$\frac{\partial \varepsilon_l}{\partial t} + \nabla\cdot(\varepsilon_l \vec{u}_l) = 0 \tag{1}$$

For Solid particles phase:

$$\frac{\partial \varepsilon_s}{\partial t} + \nabla\cdot(\varepsilon_s \vec{u}_s) = 0 \tag{2}$$

Momentum Equations.

For Liquid phase:

$$\frac{\partial(\varepsilon_l \rho_l \vec{u}_l)}{\partial t} + \nabla\cdot(\varepsilon_l \rho_l \vec{u}_l \vec{u}_l) = -\beta(\vec{u}_l - \vec{u}_s) - \varepsilon_l \nabla p + \varepsilon_l \rho_l \vec{g} - \vec{F}_{ad,l} \tag{3}$$

For Solid particles phase:

$$\frac{\partial(\varepsilon_s \rho_s \vec{u}_s)}{\partial t} + \nabla\cdot(\varepsilon_s \rho_s \vec{u}_s \vec{u}_s) = -\beta(\vec{u}_s - \vec{u}_l) - \varepsilon_s \nabla p + \varepsilon_s \rho_s \vec{g} - \vec{F}_{ad,s} \tag{4}$$

In the above equations, ε represents the volume fraction, $\vec{u}$ the velocity vector, ρ the density, p the pressure, β liquid–solid interphase drag coefficient, and F_{ad} the additional force. The l and s subscripts are used to denote liquid and solid phases in the model.

Also, to characterize the non-Newtonian drilling fluid behavior, the Power Law model was implemented. For the incompressible fluids, the relation between shear stress and rate of deformation is defined by:

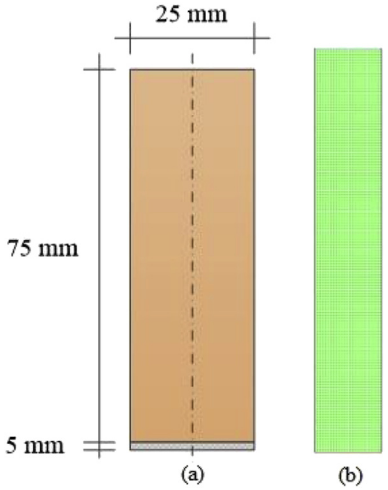

Fig. 1. Geometry (a) and computational mesh (b) of filtration model 1.

$$\tau = -\mu\dot{\gamma} \tag{5}$$

For the Power-law model, the governing equation is as shown below:

$$\eta = -m\dot{\gamma}^{n-1} \tag{6}$$

$$\dot{\gamma} = \left|\sqrt{\frac{1}{2}(\dot{\gamma}\cdot\dot{\gamma})}\right| \tag{7}$$

The numerical solution of the all modeling equations are solved directly by the FLUENT software using finite volume method.

2. CFD model for validation

2.1. Model description

In order to validate the application of CFD in simulation of filter cake formation, based on the experiment conducted in the literature (Saha, 2009) a transient CFD simulation of single pressure filtration cell was set up. Fig. 1 (a) shows the geometry of the filtration cell and Fig. 1 (b) shows the half domain generated mesh. The model is symmetric in nature and hence to reduce the run time with same accuracy in results, it is simulated in half domain.

The entire domain is divided in two parts of the drilling fluid flow area and the porous zone area. Initially, the multiphase drilling fluid flow zone was defined to have mud with 0.185 volume fraction for the solid particles and 0.815 for water phase. The fluid behavior was modeled using Power Law model. The porous media permeability was considered 135 mD which is calculated using the equation (8), based on the value of porosity and the mean solid particle diameter.

Table 1
Parameters for different Models.

Parameters	Current Model	Kabir Model
Thickness (mm)	5 mm	2.5 mm
Permeability of porous zone (mD)	135	135
Density of drilling fluid (kg/m^3)	1248	1248
Solid Fraction	0.185	0.185
Mean diameter of particles (microns)	40	40