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Numerical investigation of filter cake formation during concentric/eccentric drilling

Seyed Mohsen Hashemzadeh, Ebrahim Hajidavalloo *

Department of Mechanical Engineering, Shahid Chamran University of Ahvaz, Ahvaz 61355, Iran

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ABSTRACT

This paper deals with numerical study of filter cake formation and fluid loss on the borehole walls during an over-balanced drilling operation. Filter cake formation is a result of three interlinked phenomena; free flow of drilling fluid in the annulus, porous flow of filtrate through the formation and mud solids deposition on the well's wall. A numerical approach is developed for modeling and simulation of the cake growth, in which, initially, a three-dimensional non-Newtonian flow field of power law drilling mud is computed using finite difference method, and then, radial permeation of the filtrate and the rate of cake growth is accomplished by an explicit Runge-Kutta method. Extensive computer runs was carried out to investigate the effect of free flow parameters on the cake thickness profile and the simulation results indicated that, unexpectedly, increasing drill string rotation in a concentric case (within the conventional range of parameters for drilling operation) has almost no effects on cake thickness and permeate velocity. By increasing eccentricity, the effect of drill string rotation increases and a maximum and minimum cake thickness occurs in widening and narrowing gap, respectively. However, this impact can be neglected in high rotation rate. The effect of drill string and particle radius was studied as well.

1. Introduction

In the drilling process of oil wells, fluid is continuously injected from a surface mud tank and flows through the drill string, and back to the mud tank through the annular space between the wellbore wall and the drill string. In over-balanced drillings, due to the pressure difference between the drilling fluid and formation, one can observe a mud filtration, which means the mud solids in the drilling mud are sedimented on the sides of the well, while they are penetrating into the formation. Therefore, as shown in Fig. 1, a layer of mud cake gradually develops on the sides of a wellbore wall. Fortunately, the presence of mud cake on the sides of the formation is a beneficial occurrence, as it can reduce the amount of filtrate, which subsequently decreases the formation damage. On the other hand, thick filter cake features several demerits, such as: decreasing the efficient well diameter, excessive torque when rotating the drill string, and excessive drag when pulling it. Hence, due to its important effect, it is advantageous to be able to predict the cake growth during drilling operation.

There are large number of literature about filter cake formation. Williams (1939) investigated cake filtration using a lab well model and showed that filtration rate, which is a function of pressure difference, mud flow and mud characteristics, reaches to a constant value after a short time.

Prokop (1952) conducted a laboratory experiment for both dynamic and static cases of radial filtration of drilling mud. He probed the governing principles of the formation of mud cake and showed that in dynamic case, filter cake formation depends not only upon filtration characteristics of the mud, but also upon the erosion action of the drilling fluid.

Zinati et al. (2009) developed a model for cake formation along the borehole walls during produced water reinjection under several simplifying assumptions, and showed that increasing particle size lead to a lower cross-flow velocity along the well.

Opedal et al. (2013) studied filter cake erosion using a rotating propeller experimentally and showed that increasing rotation rate will decrease the cake thickness. Furthermore, their results show that the cake formed in high rotation velocity, exhibits a slower erosion rate in contrast with the one in low rotation rate.

Jiao and Sharma (1994) conducted experimental study on cross-flow filtration and expressed that by increasing cake thickness, smaller particle size are able to deposit on the cake surface. Moreover, they showed that there is critical permeability, below which no filter cake formed on the filter surface.

Under directional or inclined drilling conditions, gravity pulls the drill string downward causing the annulus to become eccentric. In spite of the fact that there are large numbers of

* Corresponding author.
E-mail addresses: m-hashemzadeh@mscstu.scu.ac.ir (S.M. Hashemzadeh), hajidae@scu.ac.ir (E. Hajidavalloo).

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Nomenclature

C_n	Correction factor to stokes' law in normal direction.
D_p	Particle diameter (m).
e	Eccentricity.
F_g	Buoyant force (N).
F_L	Lateral lift force (N).
F_n	Normal force to cake surface (N).
F_p	Permeating force (N).
F_s	Shear force (N).
F_t	Tangential force to cake surface (N).
g	Gravitational acceleration (m/s^2).
h	Cake thickness (m).
h_0	Cake thickness at the angle of 0^o (m).
H_{max}	Maximum protrusion height (m).
K	Permeability (m^2).
K_C	Cake permeability (m^2).
K_f	Formation permeability (m^2).
k	Consistency index.
n	Power-law index.
P	Pressure drop $(Pa.\ m^{-1})$.
p	Pressure (Pa).
Q	Volumetric flow rate (m^3/s).
r	Radius (m).
r_{eff}	Effective radius of particle (m).
R_i	Radius of outer cylinder (m).
R_o	Radius of inner cylinder (m).
r_p	Particle radius (m).
t	Time (s).
u	Fluid velocity (m/s).
u_L	Lateral migration velocity (m/s).
u_p	Permeating fluid velocity (m/s).
w	Cross flow velocity of drilling fluid (m/s).

Greek letter

α	Decay constant $(1/s)$.
β	Adhesion probability.
ε_c	Volume fraction of solids in cake.
ε_s	Volume fraction of solids in drilling mud.
κ	Radius ratio (R_i/R_o).
μ	Fluid viscosity $(pa.\ s)$.
Ω_i	Angular velocity of drill string (rpm).
ρ	Fluid density (kg/m^3).
θ	Angle (degree).

Subscript

c	Cake.
f	Formation.
l	Liquid.
s	Drilling mud.
z	Axial direction.

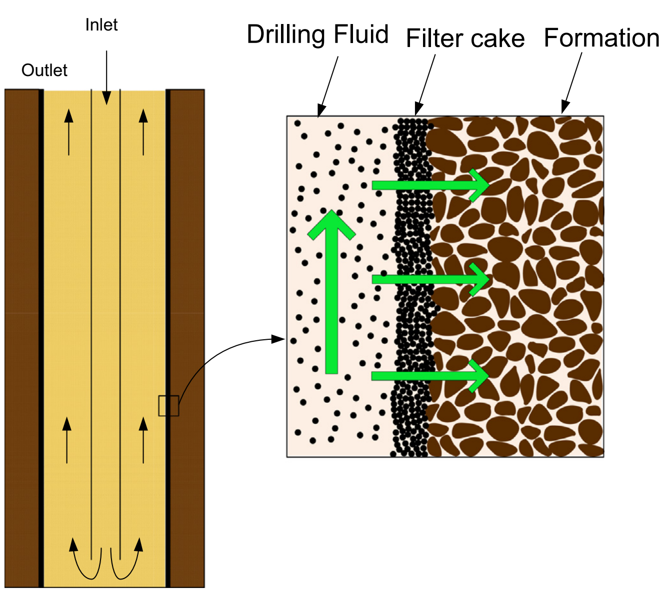

Fig. 1. An overview of the drilling process and formation of the filter cake.

literatures about filter cake formation, the effect of eccentricity and other flow parameters on the filter cake is almost neglected. However, Fisher et al. (2000), for the first time, simulated the process of cake filtration considering eccentricity using a numerical model. They scrutinized the impact of Power-law index, and the deviation of the drill string from the center of the well, and revealed that as the eccentricity increases, the thickness profile of the cake loses its symmetry. Moreover, thickness of the cake enlarges with the growth of the Power-law index.

Although Fisher et al. (2000) studied some aspects of cake formation but still there are a great deal of room for more analysis of this phenomenon. For instance, the effects of operational parameters such as rotational speed of drilling string and radius ratio on the cake formation have not been studied yet. In the present article, a numerical approach was taken into account to simulate three-dimensional free flow of non-Newtonian mud in the annulus, porous flow of filtrate through formation and cake formation on the wellbore wall, and the effects of inner cylinder rotation, particle size and eccentricity of drilling string on the cake formation were studied.

2. Modeling

To prepare a model for cake formation process, three simultaneous phenomena should be formulated: (i) Free flow of non-Newtonian drilling fluid through eccentric annulus, (ii) cake formation due to deposition of solid part of drilling fluid on the borehole walls and (iii) porous flow of liquid part of the drilling fluid into the formation. These phenomena will be explained in the following sections.

2.1. Modeling free flow in the annulus

Considering the flow in the annulus is steady, laminar, isotherm, incompressible and fully developed axial flow, one can write mass and momentum equations as follows (Cui and Liu, 1995):

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(2\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right)=\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right) \tag{2}$$