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Modelling of formation damage due to mud filtrate invasion in a radial flow system

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ABSTRACT

This paper is a sequel of our previous paper that has addressed on mud filtrate invasion into oil formation in a linear flow system. As a natural extension, here we present a mathematical model to estimate skin factor due to mud filtrate invasion into oil formation in a radial flow system. In the model, solid particle invasion and irreducible water saturation are taken into account. The present model consists of mud cake thickness model, flow rate of mud filtrate into oil formation, mud filtrate concentration, and penetration depth of mud filtrate. The estimation for reduction of oil effective permeability and skin factor near wellbore are also presented. The model is simulated and verified using three vertical well data cited from the literature. The estimation results of oil effective permeability reduction and skin factor from the model are in agreement with the data. Beside that, for the case of static filtration in radial flow, we find a critical mud cake thickness above which the rate change of thickness is increasing.

1. Introduction

Formation damage is a terminology that refers to permeability reduction in an oil or gas formation in the vicinity of wellbore. As described by Civan (2007), formation damage can be caused by various factors, including chemical, biological, hydrodynamic, and thermal interactions of formation and fluids, and reservoir deformation under stress and fluid shear. Formation damage may occur in various operations that related to exploit oil or gas from formations, including drilling, completion, workover, stimulation, and injection. Common mechanisms that caused formation damage associated with the drilling process include fluid–fluid incompatibilities, rock–fluid incompatibilities, solid invasion, phase trapping, chemical adsorption, fines migration, and biological activity (Bennion and Thomas, 1994 Bennion et al.,1996). Formation damage may occur in overbalanced and underbalanced drilling. Both of drilling technique has some advantages associated with its application. In underbalanced drilling, potential of both fluid and solid invasion from the drilling mud is minimized. Hence, this can reduce the damage. On the other hand, overbalanced drilling is safer than underbalanced drilling. Risk of blow out, fire, explosion, loss of control in underbalanced drilling is greater than overbalanced drilling. Moreover, underbalanced drilling is more expensive than overbalanced drilling (Bennion et al., 1995).

Drilling mud pressure is always maintained higher than formation pressure in an overbalance drilling. This pressure difference between mud in the annulus and oil/gas formation causes invasion of mud filtrate into the formation. Mud filtrate from water-based mud mixes with water in formation and displaces oil from the formation pores, that cause oil saturation reduction (Civan, 1994). As a result, water saturation near-wellbore zone will increase. This zone is called the invaded zone (the damaged zone) or the skin zone. Hence, oil effective permeability in the skin zone will decrease. As a result, flow resistance of oil to the wellbore will increase. This problem has been identified to cause productivity decline of a well (Bennion, 1999). A well known parameter, namely skin factor parameter, has been widely used to quantify the degree of formation damage. The skin factor depends on the reduction of oil effective permeability surrounding the wellbore and the invasion radius of mud filtrate.

Accurate estimation of invasion radius of mud filtrate and its distribution are required to estimate the damage degree due to mud filtrate invasion during drilling activity. Yan et al. (1997) have developed an empirical correlation to estimate the invasion depth of drilling mud. However, the empirical correlations cannot be used to estimate the reduction of oil effective permeability due to drilling mud filtrate invasion.

Basically, drilling mud filtrate invasion from wellbore into an oil formation can be considered as an oil displacement process by mud filtrate. A formation may contain gas, oil and water. In this

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Nomenclature

A	filter paper area (m^2)
C	mud filtrate concentration in formation (kg/m^3)
C_d	critical concentration (kg/m^3)
C_f	mud filtrate concentration in drilling fluid (kg/m^3)
C_{solid}	solid particle concentration in drilling mud (kg/m^3)
D	dispersion coefficient (m^2/s)
d_c	deposition rate (kg/s)
d_p	penetration depth of mud filtrate (m)
e_c	erosion rate (kg/s)
g	gravitational acceleration (m/s^2)
h	formation thickness (m)
k	formation permeability (m^2)
k_c	cake permeability (m^2)
k_{co}	reference permeability of mud cake (m^2)
k_{ro}	relative permeability of oil (dimensionless)
$k_{ro,max}$	empirical parameter (dimensionless)
k_s	damaged permeability (m^2)
$k_{s,mod}$	predicted damaged permeability (m^2)
k_τ	erosion rate (1/s)
m_c	mass of deposited solid particle (kg)
no	empirical parameter (dimensionless)
Pe	Peclet number (dimensionless)
p	pressure (Pa)
p_{mc}	pressure across mud cake (Pa)
q	volumetric flow rate (m^3/s)
r	position (m)
r_e	drainage radius (m)
r_s	invasion depth of mud filtrate (m)
r_w	well radius (m)
S_{or}	residual oil saturation (fraction)
S_{wir}	irreducible water saturation (fraction)
$S_{wir,p}$	predicted irreducible water saturation (fraction)
S_w	water saturation
s	skin factor (dimensionless)
t	time (s)
t_{inv}	invasion time (s)
u	filtration velocity (m/s)
V_f	filtration loss of the drilling fluid (m^3)
x_c	mud cake thickness (m)
α	empirical parameter (dimensionless)
β	empirical parameter (dimensionless)
δ	empirical parameter (dimensionless)
ν	empirical parameter (dimensionless)
Δp	overbalance pressure (Pa)
μ_f	mud filtrate viscosity (Pa s)
ϕ	formation porosity (fraction)
ϕ_c	mud cake porosity (fraction)
ϕ_{co}	reference porosity of mud cake (fraction)
ρ_c	mud cake density (kg/ms^3)
τ	shear stress of drilling fluid circulation (Pa)

case, mathematical modelling of drilling mud filtrate invasion should consider either saturation or concentration of gas, oil and water. In this paper, it is assumed that formation contains oil and water only, so the corresponding system is a two-phase system.

Many researchers have developed models to estimate drilling mud filtrate invasion into an oil formation. Mathematical modelling to this problem can be divided into two types, namely two-phase flow model and convection–dispersion model. In a two-phase flow model, the mathematical model is constructed from mass conservation and the Darcy law for water and oil phase, while in a convection–dispersion model, drilling mud filtrate invasion into an oil formation is considered as a single phase flow of mud filtrate. Examples of convection–dispersion model can be found in Donaldson and Chernoglazov (1987), Civan and Engler (1994), and Parn-anurak and Engler (2005).

Donaldson and Chernoglazov (1987) introduced a dispersion–convection equation to model drilling mud invasion into an oil formation. In their model, drilling mud invasion was considered as a single-phase flow of mud filtrate. Diffusion coefficient in the model was obtained from an empirical correlation. Civan and Engler (1994) developed a radial flow model for mud filtrate invasion. In addition, Civan and Engler estimated the invasion radius of mud filtrate using volumetric balance. The invasion radius model from Civan and Engler was based on assumption of an immiscible piston-like displacement of oil by mud filtrate. Furthermore, Parn-anurak and Engler (2005) developed a model to estimate filtration rate and mud cake thickness inside the wellbore. In their model, Parn-anurak and Engler assumed no solid particle invasion into the formation. In addition, the influence of irreducible water saturation was ignored in the Parn-anurak and Engler model. In fact, irreducible water saturation may vary with formation type.

In our previous work (Windarto et al., 2011), we modelled formation damage due to mud filtrate invasion in a linear flow system. In this paper we extend the model into a radial flow system. Radial flow model is more suitable to describe mud filtrate invasion from a wellbore into a formation. The invasion occurs into all directions, so the corresponding flow can be modelled as a radial flow. The model consists of mud filtrate invasion and mud filtrate concentration model in a formation. Solid particle invasion is taken into account in the mud filtrate invasion model, while irreducible water saturation is considered in the mud filtrate concentration model. In addition, a procedure for estimating damaged permeability and skin factor due to mud filtrate invasion is also presented. Further verification of the model with three vertical data cited from the literature had also been conducted.

This paper is organized as follows. Section 2 discusses mud filtrate invasion and mud filtrate distribution in a radial flow system. In the mud filtrate invasion model, solid particles invasion is taken into account. From the mud filtrate distribution model, we propose a criterion for estimating penetration depth of mud filtrate. Section 3 presents estimation of oil effective permeability reduction and skin factor due to mud filtrate invasion. Simulation and validation of the model with data from the literature are presented in Section 4. Conclusions are written in the last section.

2. Invasion and distribution model of mud filtrate in a radial flow system

2.1. Assumptions and limitation of the model

The model development uses the following assumptions as in Windarto et al. (2011), but now for a radial flow system:

(1) The water-based drilling mud is used in an overbalanced drilling of a vertical well, and the mud filtration is considered as a single-phase flow of mud filtrate.
(2) The corresponding formation is assumed homogeneous and isotropic.