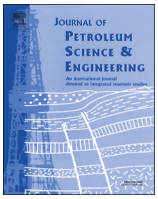
Journal of Petroleum Science and Engineering 127 (2015) 93–100

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol



Initiation and propagation of wormhole in unconsolidated rock matrix induced by long-term water injection

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A R T I C L E I N F O

Article history:
Received 9 August 2013
Accepted 21 January 2015
Available online 30 January 2015

Keywords:
Water injection
Wormhole
Porosity
Erosion
Multi-physics coupling

A B S T R A C T

The initiation and propagation of wormhole near the wellbore during the process of water injection was investigated through finite element simulations. To describe the problem, a multi-physics coupling model, in which hydrodynamics, geomechanics and erosion were coupled, was built. By constructing a reservoir model with stochastic and inhomogeneous porosity this study found that the initial porosity plays an important role in the geometry and evolution direction of wormhole. The effects on the erosion rate and wormhole area under the consideration of parameters such as flow flux, erosion coefficient and pore pressure were elucidated. Furthermore, wellbore with multi-perforations was studied to investigate possible interactions between the perforations due to Darcy flow. The simulation results show that the wormhole is more likely to form around the longer perforations. With the increase of the angle between two perforations, the wormhole around the cusp of perforations is more likely to form while the wormhole around the wellbore is restrained. This work provides an insight to guide the design of perforation pattern and application of injection in terms of optimization of the hydrocarbon production.

1. Introduction

In a reservoir, underground rocks can be regarded as a kind of porous media and hydrocarbons are accumulated in the formation rocks. After a period of producing, the natural pressure of the reservoir drops and the production rate decreases accordingly. To improve the oil recovery, various techniques are used to maintain reservoir pressure and sweep the oil towards production wells including water injection, inert gas injection and methods of enhancing oil recovery. Water injection is most commonly used. Injection wells are used to inject fresh water, sea water, formation water and water with polymer or other solute into oil reservoir. Many researchers investigated the permeability reduction of CO_2 injection (Izgec et al., 2008). Steam injection was also investigated by both experiment and simulation (Hoffman and Kovscek (2004); Gates, 2010; Pang et al., 2010). Diabira et al. (2001) studied the permeability evolution of reservoir when injecting hot water and found that porosity decreased initially due to compaction and increased later as silica dissolved. During the longtime injection, formation damage due to plug of pore was widely discussed. Moghadasi et al. (2004) conducted an experiment to study the movement of particle and deposition of porous rock matrix. They also built a theoretical model to simulate this process. Mojarad and Settari (2008) proposed a velocity-based formation damage characterization model to calculate the damage parameters. Mollakhorshidi et al. (2012) conducted a series of experiments to study the effect of salt solutions on formation damage and proposed some suggestions to minimize formation damage and increase crude oil production.

Injectivity damage can occur when the formation pore progressively plugs, resulting in pressure buildup and injectivity decline. Well washing has been a frequently-used operation for injection wells to recover the injection capacity. In some Oilfields of Xinjiang China, massive sand and rock were found in the back flow water of well washing. This may result in disastrous safety problems such as wellbore collapse. Impurities of inject fluid and sand eroded from rock near wellbore are two main sources (Abou-Sayed et al., 2005). After long term water injection, small rock particle is carried off by flow water and the porosity of rock matrix increases. In the recent literatures, the work related to the rock erosion near the wellbore caused by water injection was very lacking. In the process of production, this common phenomenon is called sand-production. Many researchers attribute the problem of sand-production to the washout or erosion of rock matrix particles induced by damage and erosion. Tang et al. (2002) proposed a flow, stress and damage model to study the rock failure phenomenon of formation. Nouri et al.

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http://dx.doi.org/10.1016/j.petrol.2015.01.032
0920-4105/

(2006) compared two stress failure criterions in order to evaluate their effectiveness. Vardoulakis et al. (1996) first proposed a hydro-erosion model to describe the sand production phenomenon. Papamichos et al. (2001), Papamichos and Vardoulakis (2005), Papamichos (2010) coupled this model with the stress of solid matrix. Wang and Wan (Wan et al., 2003; Wang et al., 2004, 2005, 2006a; Wang and Walters, 2006b) studied the effect of multi-phase flow and developed a Representative Elementary Volume (REV) model to predict the sand production and wormhole of different reservoirs. Considering the significant effect of the erosion or washout on sand production and the similarity of oil production and water injection, this process must be important to the porosity increase around the region near the wellbore during long term water injection. Cavity or wormhole can form in some loosened and erosional formation after long-term injection. Wormhole is not common in the process of water injection and there was no reported result. However, wormhole due to acid injection was studied wildly. Their methods and results can be a counterpart for discussions. The aim of acid injection technique is to create empty channels called wormhole. Some researchers studied the erosional wormhole of carbonate rock with continuum model (Liu et al., 2013; Maheshwari et al., 2013). Kalia and Balakotaiah, (2007) derived a new criterion to predict the injection rate corresponding to wormhole formation in radial flow through their simulation model. Cohen et al. (2008) studied the impact of geometry on wormhole growth with a series of 2D and 3D simulations. Tremblay and Siddiqui studied wormhole growth through the electrical image with the help of computerized tomography (CT) (Tremblay et al., 1999; Siddiqui et al., 2006).

For the first time, this study employed an erosion model to investigate the problem of wormhole due to long term water injection. Erosion was coupled with geomechanics and hydromechanics through velocity and porosity. The model was solved by using Comsol-Multiphysics, a powerful PDE-based multiphysics modeling environment (Comsol). Parameters such as flow flux, erosion coefficient and wellbore pressure were also investigated to obtain the relationship between wormhole area and the parameters. Furthermore, this work discussed the effect of perforation length and divided angle on the wormhole area and propagation direction.

2. Theoretical model and simulation method

There are two behaviors during water injection. One is the poro-mechanical behavior of the solid–fluid system and it can be described by the theory and equations of poro-elastoplasticity. The other is the erosion behavior of the solid matrix and it can be described by equations of matrix erosion.

2.1. Stress equilibrium equation for the solid matrix

The interaction between the mechanical behavior of solid matrix deforming and fluid dynamics was incorporated into the governing equations to describe the coupling effects. For the aspects of geomechanics, deforming rock skeleton under an effective stress $\boldsymbol{\sigma}^{\boldsymbol{eff}}$ and the volume-averaged pore mixture pressure P must satisfy the stress equilibrium equation:

$$\nabla \times \left(\boldsymbol{\sigma}^{\boldsymbol{eff}} - \omega P\mathbf{I}\right) = 0 \tag{1}$$

where ω is a parameter accounting for the compressibility of the sand grains. The sign convection adopted is that negative stresses are compressive and fluid pressure is always positive. The Kronecker delta tensor was given by $\mathbf{I}$ such that $\mathbf{I}_{ij} = \delta_{ij}$.

With ϕ acting as a damage parameter applied to the elastic modulus E_0 of the solid material, the effective elastic modulus E takes the form of

$$E = E_0(1-\phi) \tag{2}$$

where E_0 represents the original value of elastic modulus.

2.2. Darcy's law

For describing fluid flow, semi-empirical Darcy's law can be used to establish the relationship between pressure gradient and velocity of fluid.

$$\mathbf{v} = -\frac{\boldsymbol{k}}{\mu} \times \nabla P \tag{3}$$

where $\boldsymbol{k}$ is the effective permeability tensor that can be related to porosity via the Carman–Kozeny equation or its variant (Carman, 1956).

$$\boldsymbol{k} = \boldsymbol{k}_0 \frac{\phi^2}{(1-\phi)} \tag{4}$$

where $\boldsymbol{k}_0$ is a constant determined by experiment. For the fluid, the common continuity equations can be described as

$$\nabla \times v = 0 \tag{5}$$

2.3. Eroded solid mass generation equation

When solid particles are lifted from the solid matrix and agitated by a viscous flow, erosion phenomenon occurs. Intuitively, there must be a critical fluid velocity $\boldsymbol{v}^{\boldsymbol{cr}}$ at which sand production is initiated. Once initiated, the erosion of solid matrix depends principally on grain contact strength, local fluid drag forces, fluid pressures and availability of solids. Furthermore, it is clear that the erosion process is more intense in the regions where the porosity is small. Due to the fluid drag force, the rate of erosion follows the fluidized solid velocity. Thus based on the phenomenology and literature, a possible functional form of the mass generation can be written as

$$\frac{\dot{m}}{\rho_s} = \begin{cases} \lambda(1-\phi)\|v\| & \|v\| \ge \|v^{cr}\| \\ 0 & \|v\| < \|v^{cr}\| \end{cases} \tag{6}$$

where m is the mass of solid matrix and ρ_s is the density of solid. A similar form was used by other researchers (Vardoulakis et al., 1996; Stavropoulou et al., 1998). The solid matrix must satisfy continuity equation. Then relation between porosity and mass generation could be written as

$$\frac{\partial \phi}{\partial t} = \frac{\dot{m}}{\rho_s} \tag{7}$$

According to the above two equations, the governing equation of porosity could be obtained as below.

$$\frac{\partial \phi}{\partial t} = \begin{cases} \lambda(1-\phi)\|v\| & \|v\| \ge \|v^{cr}\| \\ 0 & \|v\| < \|v^{cr}\| \end{cases} \tag{8}$$

2.4. A benchmark

This work presented the governing poromechanics-erosion equations of multi-physics above. These equations were solved by Comsol-multiphysics. To verify the effectivity of this method, a simulation benchmark was conducted to compare this work with the experiments and simulations conducted by Papamichos et al. (2001). In this model, Darcy's flow and erosion phenomenon were considered. A two-dimensional axisymmetric reservoir was built as shown in Fig. 1. For the hollow cylinder reservoir, the following parameters were used: (1) internal radius $r_i = 1$ cm, external radius $r_e = 10$ cm, and height $H = 20$ cm, (2) initial porosity $\phi_i = 0.3$, (3) oil viscosity $\mu = 5$ cp, (4) initial permeability $k_i = 500$ md, the permeability parameter