Journal of Natural Gas Science and Engineering 32 (2016) 81–94

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Simulation of 3D multi-scale wormhole propagation in carbonates considering correlation spatial distribution of petrophysical properties

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ARTICLE INFO

Article history:
Received 10 December 2015
Received in revised form
5 April 2016
Accepted 5 April 2016
Available online 7 April 2016

Keywords:
Wormhole propagation
Matrix acidization
Petrophysical properties
Carbonate reservoir
Numerical simulation

ABSTRACT

Simulation of wormhole propagation is very critical for predicting stimulation effects of matrix acidizing and acid fracturing in carbonate reservoirs. In this paper, a 3D multi-scale wormhole propagation model is introduced, and the corresponding numerical solution details are described. Meanwhile, a variogram model is introduced to describe the correlation spatial distribution of the rock petrophysical properties, which makes simulation results of the model more realistic and reliable. An optimal parallel algorithm to numerically solve these mathematical models are discussed. Calculation results in this paper have shown that core pore structures and core minerals proportions both do significant effect on acidization simulation results. It is shown that wormholes propagate paths are highly determined by porosity distribution, and the pore-scale heterogeneity has a negative correlation with the acid volume of breakthrough. On the other hand, it is confirmed that mineral dissolution patterns change regularly with the increase of the ratio of dolomite to limestone in carbonate cores. Simulations of 3 cases have also shown that the significance of including the correlation spatial distribution of core petrophysical properties into the simulation in order to achieve a more accurate calculation of acidization effects in production and stimulation of reservoirs.

1. Introduction

According to previous studies, the wormhole dissolution patterns in acidizing and acid fracturing carbonate reservoirs can be divided into five categories: face dissolution, conical wormhole, dominant wormhole, ramified wormhole and uniform dissolution (Fredd and Miller, 2000). The dominant wormhole has the highest efficiency to break through reservoir damage zones with a least acid volume, and achieve the maximum production. However, the process of wormhole propagation includes a series of complicated physical chemical transportations and reactions, and it will become more complicated to describe and model when formation parameters such as temperature and other uncontrollable reservoir factors are considered. Therefore, in simulating carbonate reservoir acidization, not only the influence of controllable parameters (the optimal displacement parameters of acid, etc.) on wormhole propagation should be studied, but also various uncontrollable parameters (temperature and reservoir heterogeneity factors, etc.) should be included. McDuff et al. (2010) did wormhole experimental studies on radial flow at large scale. Their studies were different from the previous work because they were mainly concerning on field applications of acidizing. Because experimental studies tend to pay more attention on investigating the mechanisms, those parameters obtained through lab experiments are hard to directly use or even cannot be used to guide the optimization of acidization design in oilfields, thus a variety of wormhole prediction mathematical models have been developed to solve the complicated physical and chemistry reaction-transport problems in practical engineering. Hoefner and Fogler (1988) and Fredd et al. (1998) proposed a network model, but their simulation results were did not match their experimental results well. Buijse (2000) and Gdanski (1999) proposed a capillary tube model. However, the model assumed that the tubular wormhole already existed, which did not under the actual situations. Liu et al. (1997) and Chen et al. (1997) proposed continuum models, and Panga et al. (2005) developed the continuum model to a two-scale continuum model which can be used to describe the mechanisms of acid-rock reaction kinetics and mass transfer in linear flow very well. Based on

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http://dx.doi.org/10.1016/j.jngse.2016.04.014
1875-5100/

Panga's work, Kalia and Balakotaiah (2007) deduced a two-scale continuum model in cylindrical coordinate which was more consistent with field applications.

The two-scale continuum model has been widely used and extended in studying carbonate reservoir stimulation. Based on the continuum model, Liu et al. (2013), Ratnakar et al. (2013), Bulgakova et al. (2013) and Liu et al. (2015)performed simulations on formation of wormholes in carbonate rocks with non-Newtonian acids such as situ cross-linked acids and self-diverting acids. For vuggy-fracture-matrix media, Ziauddin and Bize (2007), Kalia and Balakotaiah (2009), Izgec et al. (2010) and Liu et al. (2012) studied the effects of vuggy and fracture on wormhole propagation in the fractured-vuggy pourous carbonate rocks. However, those researches mainly focused on two-dimensional acidization simulation in porous media, and three-dimensional simulations have s seldom been reported because the complication and time-consuming in solving 3D simulation (Cohen et al., 2008, Maheshwari et al., 2013). Notably, all of the acidization simulations mentioned above assume that rock porosity obeys the random distribution rule. While through two-dimensional simulation, MOU et al. (2014) found that dissolution patterns are quite different between the random pore distribution and realistic pore distribution. Meanwhile, spatial porosity distributions in rocks have not been considered in all existing three-dimensional simulation models. That will definitely lead to a big error as compared to the actual acidizations. Therefore, it is very necessary to further study the effects of spatial porosity distributions on acidizations.

According to the studies on mineral composition of conventional carbonate rocks, there are three types of minerals mainly contained in carbonate rocks: limestone, dolomite and insoluble minerals. Smith et al. (2012) performed experimental studies on acidizing carbonate rocks with variable amounts of minerals and highlighted the important role of carbonate contents on wormhole development. Regarding mineralogy heterogeneity, De Oliveira et al. (2012) found that local mineral distributions strongly affected PV_{BT} by modeling with CFD software, and Samadi et al. (2013) numerically studied the stimulation effect of acidization in 50% limestone & 50% dolomite reservoir. However, the effects of spatial distribution of minerals on acidization have been not discussed in all three-dimensional simulations before. This mainly focuses on developing a 3D multi-scale reactive transport model to investigate wormhole propagation mechanisms considering spatial distributions of rock petrophysical properties.

2. 3D multi-scale wormhole propagation model

The 3D multi-scale wormhole propagation model assumes that: ①Linear flow occurs in the porous media; ②Fractures and vugs are ignored, and the cores are assumed as a pure porous medium; ③ The petrophysical properties follow the rules of correlation spatial distribution; ④Carbonate rocks only contain two types of minerals: limestone and dolomite; ⑤ Ignore gravity effects on acid flow; ⑥ the linear piston-like displacement is assumed in the simulations, and ignore the influence of reservoir fluid (or brine fluid); ⑦ acid fluid is incompressible. The corresponding physical chemistry schematic diagram of the multi-scale reactive transport mechanism model in a porous medium is shown as following. (Fig. 1).

2.1. 3D Darcy flow model

The linear fluid flow in a porous medium which is described by Darcy's law is given by Ratnakar et al. (2013):

$$\|U\|^{n-1}U = -\frac{K}{\mu_{eff}}\cdot\left(\frac{\partial P}{\partial x},\frac{\partial P}{\partial y},\frac{\partial P}{\partial z}\right) \tag{1}$$

where $\|\cdot\|$ represents norm of a vector matrix, U is velocity vector (m/s), P is formation pressure (MPa), K is permeability of the reservoir ($10^{-3}\times$ um^2), μ_{eff} is effective fluid viscosity (mPa·s), x, y and z is defined as lengths of core in each direction of cartesian spatial coordinates (m).

Eq. (2) shows the fluid effective viscosity of acid fluid (Ratnakar et al., 2013). For non-Newtonian acids such as in situ cross-linked acids, the value of n is less than 1. In this paper, hydrochloric acid (HCl) system is assumed as a Newtonian fluid, and the power-law index, n = 1. Therefore, Eq. (2) can be simplified as $\mu_{eff}=\mu_0$.

$$\mu_{eff} = \frac{\mu_0}{12}\left(9+\frac{3}{n}\right)^n (150K_{ten}\phi)^{(1-n)/2} \tag{2}$$

where Φ is core porosity (dimensionless), n is power-law index of the acid fluid. K_{ten} is rock permeability tensor. μ_0 is the base viscosity of live acid from experiments (mPa·s).

The mass balance or continuity model of acid in 3D cartesian spatial coordinates is given by:

$$\frac{\partial\phi}{\partial t}+\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial \xi}{\partial z}=0 \tag{3}$$

2.2. 3D reactive transport model

In order to track concentration of hydrogen ion, the model to describe hydrogen ion is shown as follow:

$$\begin{aligned}&\frac{\partial\left(\phi C_f\right)}{\partial t}+\frac{\partial}{\partial x}\left(uC_f\right)+\frac{\partial}{\partial y}\left(vC_f\right)+\frac{\partial}{\partial z}\left(\xi C_f\right)\\&=\frac{\partial}{\partial x}\left(\phi D_{ex}\frac{\partial C_f}{\partial x}\right)+\frac{\partial}{\partial y}\left(\phi D_{ey}\frac{\partial C_f}{\partial y}\right)+\frac{\partial}{\partial z}\left(\phi D_{ez}\frac{\partial C_f}{\partial z}\right)\\&\quad-\sum_m R_m(C_s)a_{vm}\end{aligned} \tag{4}$$

where D_e is effective diffusion coefficient in the acid phase (m^2/s), C_f is the cup-mixing mass concentration of the acid in liquid phase (kmol/m^3), a_{vm} is surface area per unit volume of the mth mineral phase (m^2/m^3) in the core available for reaction, $R_m(C_s)$ is rate of the dissolution reaction for the mth mineral reaction (kmol/s m^2).

For a single step irreversible reaction, $R_m(C_s)$ has been described as (Panga et al., 2005; Kalia and Balakotaiah, 2007; Liu et al., 2012):

$$R_m(C_s)=k_{cm}\left(C_f-C_s\right) \tag{5}$$

where k_{cm} is mass transfer coefficient of the mth mineral in aqueous phase (m/s), C_s is the cup-mixing mass concentration of the acid at fluid-solid interface (kmol/m^3).

It should be note that the aqueous phase is always at equilibrium state with present minerals here, calcite and dolomite. And hydrogen ion activity is introduced into the above partial liquid equilibrium equation to describe the reaction under equilibrium conditions (Liu et al., 2015). The equation total dissolution reaction rate of the mth mineral with an activity is simplified as:

$$R_m(C_s)=\frac{k_{cm}k_{sm}\gamma_{H^+,s}}{k_{cm}+k_{sm}\gamma_{H^+,s}}C_f \tag{6}$$