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Carbonate acidizing: Modeling, analysis, and characterization of wormhole formation and propagation

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ABSTRACT

Matrix acidizing is a common practice in well stimulation to increase the permeability of carbonate formations and then facilitate the oil flow to the wellbore. The acidizing operation is accomplished by injecting reactive fluids to dissolve and disperse the rock while creating highly conductive wormholes. Modeling and numerical simulations of carbonate acidizing present an effective tool to determine dynamic behavior trends and when supported by experimental studies may provide useful guidance to design successful matrix treatment.

In this work, we develop and validate a 3D core scale predictive model for carbonate acidizing, benchmarked by linear core flooding experiments. The model employs the two-scale continuum approach to simulate reactive fluid flows and wormhole propagation in carbonate rocks. It takes CT porosity scans along with detailed knowledge of measured reaction kinetics to describe the reactive transport of acid species at Darcy scale and accounts for the underlying physics at the pore-scale through structure–property relationships which couple the local permeability, porosity, pore radius, and solid–fluid interfacial area.

The present model shows a good capability to qualitatively capture the experimentally observed wormhole morphology and quantitatively predict the pore volume to breakthrough. Furthermore, we employ the two- and three-dimensional versions of the cluster multiple labeling technique to characterize the wormhole formation and penetration for varying operating conditions. Distinctive and informative features in terms of wormhole distribution and size are obtained. The three-dimensional clustering technique show the generation of more wormholes with higher ability to sustain during the acidizing process when injecting the acid at the optimal rate. The two-dimensional analysis enables to track the growth and death of transverse wormholes. It is used to show the effect of rock heterogeneity in creating highly branched wormholes, useful in providing more low-resistance paths for the oil to flow from the reservoir to the wellbore. Finally, we introduce a novel concept for real-time monitoring and control of matrix acidizing. This concept is based on performing resistivity measurements while injecting acid to track wormhole penetration. These measurements are observed to be informative of the acidizing regime. The objective is to show the potential use of resistivity logging tools in the field to achieve successful matrix treatment.

1. Introduction

Acidization is a common practice in well stimulation to increase the permeability of the carbonate rocks and then facilitate the oil flow to the wellbore. The acidizing operation is accomplished by injecting reactive fluids (commonly hydrochloric acid) below the fracturing pressure of the formation to dissolve and disperse the rock while creating highly conductive wormholes. Experimental and numerical studies (Hoefner and Fogler, 1988; Daccord et al., 1993; Izgec et al., 1993; Fredd and Fogler, 1998; Xu et al., 1998; Gong and El-Rabaa, 1999; Buijse, 2000; Fredd, 2000; Fredd and Miller, 2000; Golfier et al., 2001; Panga et al., 2002, 2004, 2005; Kalia and Balakotaiah, 2007; Tardy et al., 2007; Ziauddin and Bize, 2007; Cohen et al., 2008; Kalia and Balakotaiah, 2009; Izgec et al., 2010; Kalia and Balakotaiah, 2010; Ratnakar et al., 2012; de Olivera et al., 2012; Liu et al., 2013; Maheshwari and Balakotaiah, 2013; Maheshwari et al., 2013; Ratnakar et al., 2013; Qiu et al., 2013; Maheshwari et al., 2014; Tansey, 2014; Qiu et al., 2014) have shown the strong dependence of the dissolution structure and wormhole morphology on the injection rate of acid. At low injection speeds, the acid is entirely spent before penetrating into the medium and then the whole face of the formation is dissolved (face dissolution).

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Nomenclature

L	core length
x	axis along the injection direction
t	time
Δt	time step
α_y	core aspect ratio
α_z	core aspect ratio
r_0	initial pore radius per unit volume
a_0	initial interfacial area per unit volume
K_0	initial average permeability
k_s	dissolution reaction rate
D_m	acid diffusivity
ρ_s	rock density
μ	acid viscosity
Sh	Sherwood number
ϵ_0	initial average porosity
β	pore-broadening parameter
γ	pore-connectivity parameter
$\Delta\epsilon_0$	porosity heterogeneity
α_{os}	constant in dispersion coefficient
λ_X	constant in longitudinal dispersion coefficient
PVBT	pore volume to breakthrough
ρ	resistivity
S_w	water saturation
V	voltage
A	cross-section area
f	fluid
d	hole diameter
$\mathbf{U}$	Darcy velocity vector
(y, z)	axes perpendicular to the injection direction
η	length ratio
$\mathbf{n}$	normal unit vector
ϵ	porosity
P	pressure
$\mathbf{K}$	permeability tensor
C	concentration
$\mathbf{D}_e$	dispersion tensor
α	dissolving power of acid
k_c	mass-transfer coefficient
r_p	mean pore radius
P_e	back pressure
U_0	injection speed of acid
C_0	inlet concentration of acid
D_a	the Damkohler number
ϕ^2	the pore-scale Thiele modulus
Φ^2	the macro-scale Thiele modulus
N_{ac}	the acid capacity coefficient
λ_T	constant in transversal dispersion coefficient
a_v	solid–fluid interfacial area
n, m	Archie's exponents
χ	volume fraction
I	current intensity
a	acid
D	core diameter
l	hole length

At very high injection speeds, the acid may penetrate deep into the formation but still the reaction of acid takes place over a large region, yielding a uniform increase in the porosity (uniform dissolution). Injecting acid at optimum rates leads to the formation and propagation of wormholes in the carbonate formation. A successful matrix treatment requires the production of deep and thin wormholes with minimal volume of injected acid that will enhance the oil productivity. Several numerical studies and core flooding experiments (Hoefner and Fogler, 1988; Daccord et al., 1993; Izgec et al., 1993; Fredd and Fogler, 1998; Xu et al., 1998; Gong and El-Rabaa, 1999; Buijse, 2000; Fredd, 2000; Fredd and Miller, 2000; Golfier et al., 2001; Panga et al., 2002, 2004, 2005; Kalia and Balakotaiah, 2007; Tardy et al., 2007; Ziauddin and Bize, 2007; Cohen et al., 2008; Kalia and Balakotaiah, 2009; Izgec et al., 2010; Kalia and Balakotaiah, 2010; Ratnakar et al., 2012; de Olivera et al., 2012; Liu et al., 2013; Maheshwari and Balakotaiah, 2013; Maheshwari et al., 2013; Ratnakar et al., 2013; Qiu et al., 2013; Maheshwari et al., 2014; Tansey, 2014; Qiu et al., 2014)have examined the impact of other operating conditions and parameters such as the acid properties, reaction kinetics and mass transfer coefficient, and rock heterogeneity and properties (lithology, porosity, pore structure, etc) of the carbonate formation on the dissolution process and wormhole propagation.

Over the last few decades, there has been a great interest in the modeling and numerical simulations of reactive dissolution of carbonate rocks. Mathematical models based on different approaches (Hoefner and Fogler, 1988; Daccord et al., 1993; Izgec et al., 1993; Fredd and Fogler, 1998; Gong and El-Rabaa, 1999; Buijse, 2000; Fredd, 2000; Fredd and Miller, 2000; Golfier et al., 2001; Panga et al., 2002, 2004, 2005; Kalia and Balakotaiah, 2007; Tardy et al., 2007; Ziauddin and Bize, 2007; Cohen et al., 2008; Kalia and Balakotaiah, 2009; Izgec et al., 2010; Kalia and Balakotaiah, 2010; de Olivera et al., 2012; Ratnakar et al., 2012; Liu et al., 2013; Maheshwari et al., 2013; Maheshwari and Balakotaiah, 2013; Ratnakar et al., 2013; Ghommem et al., 2014; Maheshwari et al., 2014; Tansey, 2014) have been developed and proposed to address the modeling challenges related to the coupling of chemical reaction with fluid flows in porous media and the interaction between acid transport and heterogeneities encountered at different scales (pore to reservoir scale). These include capillary-tube, pore-network, and continuum approaches. These models present an effective complement to core flooding experiments in providing baseline and guidance for the optimization and control of the matrix acidizing process. The reader is referred to Panga et al. (2002, 2004, 2005) and Maheshwari et al. (2013) for a detailed review of the acidizing models along with their assumptions and range of validity. Capillary-tube models (Daccord et al., 1989, 1993; Buijse, 2000) assume pre-existing wormholes with specified shapes and simulate the acid reaction and transport inside these predefined wormholes. These models do not have the capability to capture the wormhole initiation process and cannot predict the wormhole size and density during the acidizing process but can provide some information on the impact of the control parameters on the dissolution process. In pore-network models (Hoefner and Fogler, 1988; Fredd and Fogler, 1998; Xu et al., 1998; Tansey, 2014),the carbonate formation is represented by an aggregation of particles which are connected through bonds and then the dissolution process is described from the pore scale. While these models were successful in qualitatively predicting the experimentally observed trends (occurrence of optimum injection rate), the minimum pore volumes to breakthrough were observed to be much higher than that found based on laboratory core flooding studies mainly due to the small network size (Fredd and Fogler, 1998). In the continuum models (Panga et al., 2002, 2004, 2005; Kalia and Balakotaiah, 2007, 2009, 2010; Liu et al., 2013; Maheshwari and Balakotaiah, 2013; Maheshwari et al., 2013; Ratnakar et al., 2013; Ghommem et al., 2014; Maheshwari et al., 2014), the reactive dissolution of carbonate formation is simulated at Darcy scale. The Darcy-scale representation of the reactive flow is completed by a pore-scale model that describes the underlying physics