Numerical Investigation of Acid Wormholing During Acidization of Carbonate Formations

Fereshteh Samadi, Feridun Esmaeilzadeh, Dariush Mowla
School of Chemical and Petroleum Engineering, Shiraz University, Shiraz, Iran

Abstract

Matrix acidizing is a technique to stimulate wells for improving well inflow performance. In this treatment, acid solution is injected into the formation at pressure below the rock failure pressure to dissolve some of the minerals to increase permeability of carbonates near the wellbore. In this work, matrix acidizing has been simulated in the radial 3-D domain using continuum/average model. The reaction kinetics has been considered to be nonlinear at solid-liquid interface. The reservoir is considered as a heterogeneous media and the effects of acid molecular diffusion, acid convection by fluid bulk and acid reaction with rock in porous media are considered. Different dissolution patterns observed in the experiments are shown by numerical simulation results. To validate the model, one set of acidizing field data of well-5 Sarkhoon was used. Results are discussed in term of skin factor. In particular, the change in the dominant wormhole growth dynamic is investigated during wormhole propagation around the wellbore.

1. Introduction

Stimulation of oil wells in carbonate reservoirs using an acid is a common practice to enhance oil flow to the wellbore. Because the surface reaction rates are very high and mass transfer often plays the role of limiting step locally, highly nonuniform dissolution patterns are usually created. As the acid penetrates into the porous rock, it dissolves the rock creating conductive channels known as wormholes. The wormholes bypass the damaged zone around the wellbore, leaving highly permeable channels for the oil to flow back after the treatment. The formation of these patterns depends on the injection rate of the acid and the volume injected. In addition, several other factors such as the type of acid, mineralogy and heterogeneity of the formation, temperature, etc. can affect wormhole formation and propagation.

The history of acidizing dates back to 1895, when the Ohio Oil Company acidized both oil and gas wells with significant increases in production. But the academic studies on the acidizing have been initiated since last three decades. Daccord [1], Hoefner et al. [2], Hung et al. [3], Williams et al. [4], Fredd et al. [5] and Wang et al.[6], studied on the injection of acid into linear core at constant volumetric rate.

Wang et al. [6], measured the volume of acid required to achieve wormhole penetration through a core (breakthrough) and calculated the acid fluxes about the wormhole that develop during the experiment to find the flux at the tip as well as along the sides of the wormhole.

A subsequent study by Bazin et al. [7], showed the importance of core length in laboratory studies. As the length of the dominant wormhole increases, the amount of acid lost through the lateral boundaries increases, thereby reducing the volume of acid reaching the tip and ultimately resulting in an acid flux at the tip that is too small to initiate wormholes there. In such a case, the wormhole can extend only slowly while it is also being enlarged.

Panga et al. [8], developed a two-scale continuum model to describe transport and reaction mechanisms in reactive dissolution of a porous medium, and used the model to study wormhole formation during acid stimulation of carbonate in the linear cores and showed to initiate dissolution patterns; it is required to introduce heterogeneity in the domain.

Also, some studies on wormhole formation in carbonates focus on acid injection into radial cores at constant volumetric rate. Extensive studies have been done on the modeling of wormhole formation in the core scale and some empirical correlations have been developed for optimum injection rate. Kalia et al. [9], used a two-scale continuum model to simulate reactive dissolution of carbonate rocks in radial flow for core scale and could derive a new criterion to predict the optimum injection rate for wormhole formation in radial flow. Some investigators tried to scale laboratory results to the field. Frick et al. [10], and Buijse [11], tried to scale the laboratory injection rate by the ratio of surface areas. In these models, the flow rate per wormhole and, consequently, the rates of transport and reaction are not consistent with those observed in the laboratory. Hence, this method does not correctly scale the wormhole structure.

Huang et al. [12], presented a method that involves scaling the injection rate by the number of wormholes formed per unit surface area.

Fredd [13], presented a model which addressed the issue of scaling laboratory data to the field by including the effects of fluid loss and wormhole competition. This model showed under typical treatment conditions, conventional matrix treatments with straight HCl cause face dissolution and provide little reduction of skin.

Cohen et al. [14], studied on how the geometry of the domain can constrain wormhole competition, and influence wormholing dynamics in a core submitted to acidizing and concluded that wormholing is not a full-scale independent process and realized that the flow rate in the dominant wormhole does not depend on geometric effects.

Izgec et al. [15], explored the effects of heterogeneity on vuggy carbonate acidizing and observed that acid propagates wormholes through vuggy carbonates much more rapidly than those in homogeneous rocks. They presented a modeling study to understand the flow in porous media in the presence of vugs using coupled Darcy and Stokes flow principles. The results demonstrate that the total injection volume to breakthrough is affected by spatial distribution, and the amount and connectivity of vuggy pore space.

The first part of this paper describes the physical model used to account for the coupling between flow and dissolution. The 3-D two-scale continuum model for describing acid flow into a carbonate porous medium under radial flow conditions is presented. The coupled system of equations is solved numerically in three dimensions using a finite volume method. In the second part, the model was applied to simulate the acidizing process in well-5 Sarkhoon located in Iran. The results were compared in term of skin factor. After that, the different dissolution patterns observed in the experiments are shown by numerical simulation results.

2. Mathematical Modeling

The average/continuum model is presented for modeling of radially wormhole formation during matrix acidizing of carbonate. The model presented here differs from existing literature models in one fundamental aspect. This model is extended for nonlinear chemistry at the solid–fluid interface (non-linear reaction kinetics) depending on the reservoir temperature.

The governing equations are:

continuity equation with nonzero divergence:

$$\frac{\partial \phi}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(ru) + \frac{1}{r}\frac{\partial v}{\partial \theta} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

The mole balance equation for acid with two concentration variables to account for the local gradients at the pore level by the coupling between the convection, dispersion and chemical reaction:

$$\frac{\partial(\phi C_f)}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(ruC_f) + \frac{1}{r}\frac{\partial}{\partial \theta}(vC_f) + \frac{\partial}{\partial z}(wC_f) =$$
$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\phi D_{eR}\frac{\partial C_f}{\partial r}\right) + \frac{1}{r}\frac{\partial}{\partial \theta}\left(\frac{\phi D_{e\theta}}{r}\frac{\partial C_f}{\partial \theta}\right) + \frac{\partial}{\partial z}\left(\phi D_{ez}\frac{\partial C_f}{\partial z}\right) - k_c a_v(C_f - C_s) \tag{2}$$

The balance between amount of solid dissolved and amount of acid consumed:

$$\frac{\partial \phi}{\partial t} = \frac{R(C_s)\alpha\, a_v}{\rho_s} \tag{3}$$

And, the solid phase mole balance which states that moles of acid in the solid-liquid interface that react with solid phase are coming from the bulk of liquid phase with concentration C_f. Driving force for this transport is (C_f-C_s). It can be thus written that:

$$k_c(C_f - C_s) = R(C_s) \tag{4}$$

Here r, θ, z and t are independent variables; u, v and w are velocity components in r, θ and z directions. D_{eR}, $D_{e\theta}$ and D_{ez} are dispersion coefficients in r, θ and z directions. C_f and C_s are acid

concentration in the bulk of fluid phase and in solid-liquid interface. ϕ is the porosity of reservoir and k_c is the local mass transfer coefficient. a_v is the interfacial area defined as fluid–solid interfacial area per unit volume of the medium and α is the dissolving power of the acid, defined as grams of solid dissolved per mole of acid reacted, $R(C_s)$ represents the rate of the dissolution reaction and ρ_s is the density of the solid phase.

The auxiliary equations are as follow:

Darcy equation:

$$(u,v,w) = \left(-\frac{K}{\mu}\frac{\partial P}{\partial r}, -\frac{K}{\mu}\frac{\partial P}{r\partial \theta}, -\frac{K}{\mu}\left(\frac{\partial P}{\partial z} - \gamma\right) \right) \tag{5}$$

Where P and K are the pressure and permeability tensor of reservoir, μ and γ represent the viscosity and specific gravity of fluid.

The term $R(C_s)$ represents the rate of dissolution reaction which is considered to be non-linear and defined as:

$$R(C_s) = k_s C_s^n = k_o \exp\left(\frac{-\Delta E}{RT}\right)C_s^n \tag{6}$$

To complete the model, in Eqs. (1)– (6), a pore scale model to relate the local permeability, average pore radius and interfacial area to the local porosity of the medium is required. The pore-scale rock properties may be related to the Darcy scale quantities through relations known as the structure–property relations. In this work, these relations are obtained by modifying the Carmen–Kozeny relation by introducing the parameter β to account for dissolution. To initiate dissolution patterns, it is required to introduce heterogeneity in the domain. In this study, the initial porosity field was perturbed by a white noise. This perturbation in the porosity leads to perturbation in the permeability field using Carmen–Kozeny equation. It is also worth noting that this perturbation does not have a strong effect on the shape of long range wormholes.

In the model, acid is assumed to be injected at constant rate into a well and pressure in the drainage radius is considered constant.

3. Model Validation

The numerical approach is validated by comparing the calculated and measured skin factor. Well no. 5 in the Sarkhoon field, is located in the south of Iran, was subjected to acidizing treatment because of low bottomhole flowing pressure. The skin factors before and after acidizing calculated by analyzing well tests results were 3.91 and -3.61, respectively.

The values of required parameters for the simulation are given in Tables 1 and 2.

Table 1: Reservoir properties			
Pressure(MPa)	Temperature (K)	Permeability (md)	Porosity (%)
16	382	5.5	10.35

Table 2: Acid injection conditions		
Type of fluid	Cumulative volume (m³)	Injection rate (m³/s)
HCl (28% wt)	36.36	8.49×10^{-3}

For this treatment, acid was used with 2% wt retarder agent. The reaction rate parameters were taken from Feyzi [16].

Using these data, the acidizing treatment was simulated by this model. An equivalent skin can be written by (Economides et al. [17]; Izgec [15]):

$$S = \left(\frac{k}{k_{wh}} - \frac{k}{k_s} \right) \ln r_{wh} + \left(\frac{k}{k_s} - 1 \right) \ln r_s + \left(1 - \frac{k}{k_{wh}} \right) \ln r_w \tag{7}$$

Considering wormholing in carbonate acidizing, we can take improved permeability, k_{wh}, sufficiently large. Then;

$$S = \frac{k}{k_s} \ln \frac{r_s}{r_{wh}} - \ln \frac{r_s}{r_w} \tag{8}$$

Eq. (8) applies until the radius of wormhole penetration exceeds the radius of damage. Later, as $k_s \sim \infty$, this equation becomes:

$$S = -\ln \frac{r_{wh}}{r_w} \tag{9}$$

Using these relations, evolution of skin was plotted versus pore volume acid injected and shown in Fig.1.
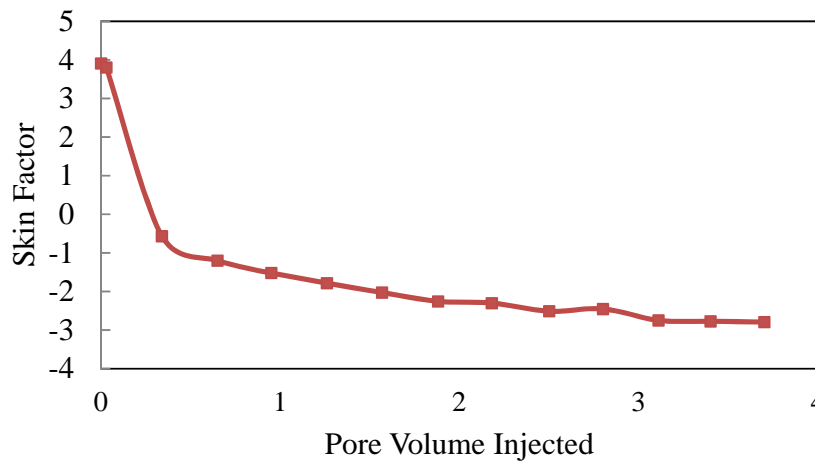

Fig. 1: Evolution of skin factor versus pore volume of injected acid

The final skin factor calculated by this model is -2.80 which the absolute error for the calculated and measured skin factor in the field is 0.81. As can be seen, the skin factor decreases sharply in the beginning of the treatment up to 1.5 pore volume of injected acid, after that the evolution of skin factor declines and the slope of Fig. 1 tends to zero. This can be explained by considering the wormhole interacting effects. In the beginning of the treatment the wormholes are small and compete with each other to grow. In this stage, the dominant wormhole length increase and thus skin factor declines sharply. When the wormhole length reaches to its critical value, the shadowing effect causes to grow the smaller wormholes, thus change in the skin factor decreases.

4. Dissolution Patterns

Fig. 2 shows results from 3D simulations of acid injection in radial flow in the damaged zone for five different injection velocities chosen to produce several dissolution regimes, from compact to uniform dissolution. For this purpose, one set of simulation was done by considering acid injection in a vertical well with a formation height of 30 m, well radius of 7 in, drainage radius of 155 m, initial skin factor of 3, damage radius of 0.9144 m, with 400 000 grid blocks. Mesh sizes was stretched around the well in the radial direction in order to most grid blocks located in the damage zone. For this illustration, we choose the following parameters: the injected concentration of hydrochloric acid is 318 kg/m^3 (28% wt), the porosity of the porous medium is 0.2 and the undamaged permeability of the porous media is 8 mD. The acid injection in the well is at constant flow rates that correspond to each dissolution patterns. It should be noted that the permeability of the damaged zone has been calculated using Hawkin's equation.

The typical dissolution patterns obtained for different Damköhler numbers are shown in Fig.2 (a)–(e). From the figure, it can be seen that by changing the Damköhler number (or flow rate), the patterns observed in the experiments of Frick et al. [18] can be simulated using the model.
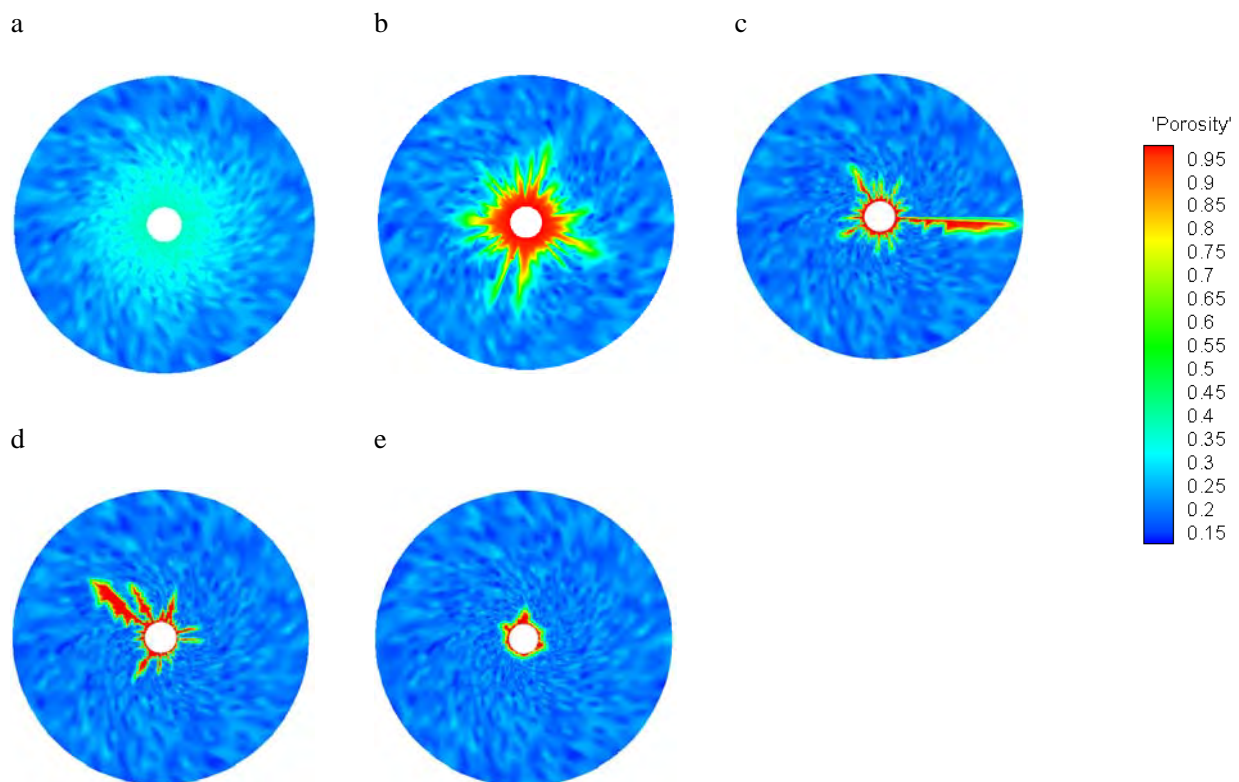

Fig. 2: Radial dissolution patterns in porosity for different Damköhler number values of: (a) Da=1; (b) Da=10; (c) Da=50; (d) Da=100; (e) Da=8000

In summary, it is expected that for injection rates that are very slow, wormholes will not form and the face of the wellbore will dissolve rather uniformly. At modest injection rates, large enough to initiate wormholes at the tip of the primary wormhole, an etch pattern is expected to

develop that shows little branching from the primary wormhole. Most of the acid is then expended in extending the primary wormhole. If the rate of acid injection is then increased, the acid fluid-loss flux into the rock matrix may be large enough everywhere or at least at many points to allow the initiation of wormholes along the boundary of the primary one. A highly ramified wormhole structure is expected at the higher injection rates.

5. Wormhole Growth

The initiation of wormholes occurs when live acid penetrates into pores present in the native rock. These pores are distributed in size and shape; therefore, the amount of acid flowing through each of the pores differs. The rate at which a given pore is enlarged by the acid depends, of course, on the amount of acid entering that pore and the fraction of the acid reacted at the walls of the pore before the acid exits and then enters other pores located downstream. Thus, even at the pore level, the processes that contribute to the creation of an etch pattern are complex, involving convection, diffusion and chemical reactions within each of the invaded pores. It has not been proved practical to consider these processes in a single pore and then attempt to consider the collective behavior to derive a macroscopic etch pattern. Fig. 3 shows wormhole growth around the wellbore in the different pore volumes of injected acid. In the beginning of the treatment the wormholes are small and compete with each other to grow. In this stage, the dominant wormhole length increase with injection. When the wormhole length reaches to its critical value, the dominant wormhole growth becomes negligible that causes to grow the smaller wormholes.

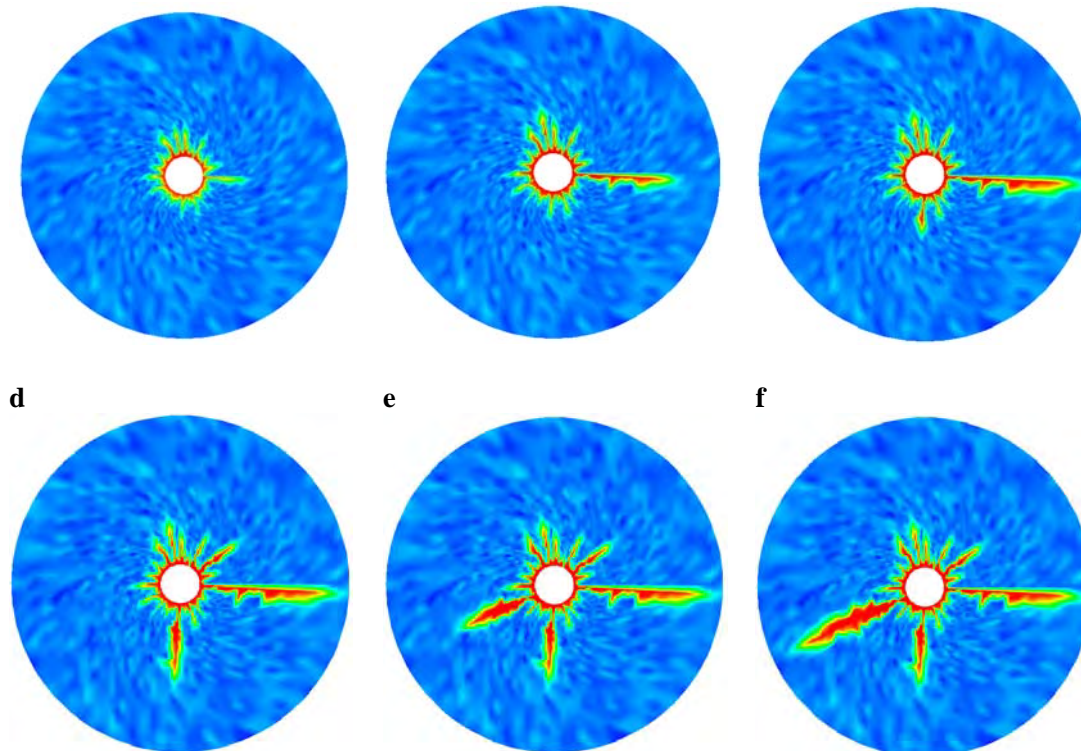**a**   **b**   **c**   'Porosity'

Fig. 3: Porosity field around the wellbore in the different pore volumes of injected acid
(a) PV_{inj}=0.82, (b) PV_{inj}=1.64, (c) PV_{inj}=2.05, (d) PV_{inj}=3.28, (e) PV_{inj}=5.125, (f) PV_{inj}=7.46

6. Conclusions

The motivation for this study was simulation of acidizing in the wellbore scale have received little attention in the literature, while they are of paramount importance for field-scale applications.

The numerical study presented in this paper, based on the use of a local non-equilibrium wellbore-scale model, extended to include nonlinear chemistry at the solid–fluid interface.

Several numerical simulations have been performed. They show that this mathematical model can reproduce all the dissolution regimes observed in the literature and could be useful in understanding the transient evolution of unstable dissolution patterns around a wellbore.

To evaluate the accuracy of the results, model was applied to a real case of well matrix acidizing which the skin factor before and after treatment were available. Since the observable consequent of the acidizing treatment is the reduction of the skin factor, thus the result from the simulation and field acidizing treatment has been compared in term of this parameter. At the beginning of acidizing treatment, the results show that the dominant wormhole length increases with the volume of injected acid and the skin factor sharply decreases until the wormhole length reaches to its critical value. After that, the shorter wormholes begin to grow. Finally, the evolutions of the wormhole competition and growth dynamic have been elucidated.

Acknowledgements

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