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Numerical modelling and analysis of reactive flow and wormhole formation in fractured carbonate rocks

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HIGHLIGHTS

- A continuum model is developed to study the reactive flow in fractured porous media with a complex fracture network.
- Numerical method for solving the developed model is described.
- The structure of the dissolution patterns is computed under various conditions.
- The effect of the characteristic parameters of complex fractures is analyzed.

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ABSTRACT

Combining the two-scale continuum model and the discrete fracture network model, a continuum-based model is developed that calculates the reactive flow of acid in carbonate rock with a complex fracture network. The locations of fractures in the model are explicitly defined and the method can capture complex geometric relationships. The governing equations are discretized by the finite-volume method, where the diffusion term and convection term are discretized using the two-point flux approximation (TPFA) scheme and the upwind scheme, respectively. The physical domain is discretized by Delaunay triangulation. To keep the robustness and efficiency of the TPFA scheme, the optimization algorithm is used to move the centroid node of the control volume to improve the orthogonality of the grids. Numerical simulations of reactive flow in 2D fractured porous media, in cases with simple and complex fracture arrays, under linear and radial flow conditions, are presented. In particular, a sensitivity analysis of the dissolution process with respect to the presence of fractures, fracture aperture, fracture distribution, and acid injection rate, is conducted.

1. Introduction

Matrix acidizing is a common stimulation treatment for improving the flow characteristics of the near-wellbore region in carbonate reservoirs. It consists of injecting acid into the formation around some interval of the wellbore at pressures below the fracturing pressure. During the process, acid penetrates into the pores of the formation and dissolves some rock components such as cements or grains, and usually, if successful, creates wormholes, which can bypass a potentially-damaged zone around the wellbore, providing some highly permeable channels for hydrocarbon flow into the well. The productivity of a well can be enhanced significantly by acidizing, especially when near-wellbore damage is present and has motivated the decision to undertake this treatment. If a well does not have drilling-caused damage, the economic benefit of performing acidizing stimulation is less obvious, so matrix acidizing is generally applied only to a well that has a high skin factor which cannot be attributed to the mechanical aspects of the completion, such as partial penetration, perforation efficiency and so on (Economides and Nolte, 2000). Nevertheless, this rule is commonly broken when natural fractures are present in the formation. In naturally fractured reservoirs, injected acid may penetrate to a sufficient distance to yield a productivity enhancement greater than that normally expected from an acidizing treatment in un-fractured carbonate reservoir (Economides and Nolte, 2000; Liu et al., 2017). For this reason, acidizing is a widely conducted stimulation treatment in fractured carbonate reservoirs to increase the production (Bratton et al., 2006). Since the details of acid flowing through the fractured reservoir are different from the case of general matrix acidizing in a comparable un-fractured reservoir, a good understanding of the effect of

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natural fractures on the acidization process is needed to improve the design of the operation.

Numerous experimental studies have been conducted to understand the dissolution process in fractured cores (Detwiler, 2008; Detwiler et al., 2003; Dijk et al., 2002; Dong et al., 1999; Durham et al., 2001; Gouze et al., 2003; Polak et al., 2004). In laboratory experiments, artificial fractures are designed by contacting two rock samples together along a quasi-planar interface, and the fracture aperture is represented by the gap between the samples (Dong et al., 1999). The surfaces of the core samples, which compose the "fracture" walls, are either smooth or rough. Before and after the dissolution experiments, the aperture fields are quantified with digital reconstruction techniques, such as high-resolution X-ray computed tomography (CT) (Gouze et al., 2003) and nuclear magnetic resonance imaging (NMRI) (Dijk et al., 2002). The influence of parameters, such as the roughness of the fracture wall, the reaction kinetics, and the mineral dissolution rate, on the dissolution pattern can therefore be investigated. These experiments provide a direct observation of the consequences of dynamic acid flow and dissolution in rock fractures, and are fundamental for the mathematical model development to predict the reactive flow process in fractures. For example, Detwiler et al. (2003) conducted a series of reactive flow experiments on artificial fractures and concluded that the dissolution-induced evolution of aperture variability is determined by the relative magnitude of the diffusion and advection of the reactants as well as the mineral dissolution rate. In addition, two types of geometrical changes in fractures after being exposed to reactive fluid are observed (Deng et al., 2016). One is the enlargement or reduction of the fracture aperture, resulting from dissolution or precipitation of minerals around the fractures (Deng et al., 2016; Detwiler, 2008; Durham et al., 2001). The other one is the formation of a porous altered layer in the near-fracture region, resulting from the reactant dispersion into the rock matrix and the fast reaction rate (Deng et al., 2016; Ellis et al., 2013; Noiriel et al., 2007). However, the experimental works have so far only investigated the dissolution process in a single fracture. The effect of the presence of multiple fractures, especially those which exist in a complex fracture network, relative to the dissolution process, have not yet been investigated through experiment, and hence a numerical method is needed.

The numerical models developed to investigate the reactive flow in fractured rocks can be classified mainly into three types: (1) single fracture model (Deng et al., 2016; Detwiler and Rajaram, 2007; Dong et al., 2002b; Hanna and Rajaram, 1998; Hill et al., 2001; O'Brien et al., 2003; Szymczak and Ladd, 2009; Upadhyay et al., 2015), (2) fracture network model (Dong et al., 2001; Dong et al., 2002a), and (3) pseudo-fracture model (Kalia and Balakotaiah, 2009; Yuan et al., 2016). Here, we give a brief review of these models. In the single fracture model, only one fracture is considered, which is generated by contacting two surfaces together with a gap between them. The two surfaces can be either smooth or rough, and the resulting aperture is assumed to depend on a spatial variable. The model is based on mass conservation for fluid flow and reactant transport, and equations for chemical kinetics within the fracture space. The matrix leakoff is considered by introducing a source/sink item. The pressure, acid concentration, and fracture aperture as functions of space and time can be calculated by numerical simulation. Different dissolution patterns, which depend on the physical and chemical characteristics of the fracture-fluid system, are obtained, and the results have a good agreement with those observed in the experiments. These models provide a useful starting point for numerical analysis of reactive flow in fractured porous media. However, a single-fracture model cannot explain the dissolution process in real fractured rock, in which the fracture distribution is complex.

In the fracture network model, the matrix is ignored and the fractured medium is represented by a system of intersecting fractures, which provides the pathway for acid transport and dissolution. The fracture network model is an extension of the single fracture model and is based on the assumption that acid always creates a channel in only one main flow path in the fracture network. Acid flowing into tail fractures (fractures that are not on the main flow path) and matrix is calculated by using a leakoff coefficient. Subject to these assumptions, the flow and dissolution in those fractures that are not connected with the wellbore cannot be characterized in this model. In addition, as the main flow path should be pre-determined and the acid can only flow along this main flow path, the branching characteristic of the dissolution pattern cannot be described. However, this model proposes a field-scale design method for well treatments in a fractured reservoir and demonstrates that acidizing in a fractured reservoir is more efficient than in un-fractured reservoir, as observed in many carbonate acidizing treatments.

In pseudo-fracture models, the fractures are treated as a type of matrix that has anomalously-high porosity, and the fracture is represented by one mesh cell whose thickness is greater than the actual fracture aperture. These models are actually the same as those matrix acidizing models in terms of the mathematical equations. Therefore, they can naturally couple the acid flow and reaction in matrix with that in the fractures. Pseudo-fracture models provide an easy way to investigate the effect of the presence of fractures and the fracture location and orientation on dissolution dynamic, and the results are convenient for comparison with the results of matrix acidizing simulations. However, these models just set up some high-porosity channels in a domain of matrix to represent the fractures, and they lead to the need to create a finer grid to represent the fracture with one mesh cell, which will undoubtedly increase the computational time. In addition, this sort of model is particularly unsuited for use if one wished to extend the analysis to include concurrent geomechanical effects related to the fracture system changes caused by the acidizing (this will be addressed in our future work). All of these shortcomings make pseudo-fracture models inappropriate for simulating the reactive flow in porous media that have complex fracture arrays.

The main aim of this paper is to develop a reactive-transport simulation model that permits an evaluation of the effect of multiple, intersecting fractures on reactive flow in carbonate rocks. This can be accomplished by the combination of the two-scale continuum model developed by Panga et al. (2005) with the methods of a discrete fracture model. For the sake of convenience, we denote the combined new model, described below, as the two-scale discrete-fracture continuum model (TSDFC). The locations of fractures in the TSDFC model are explicitly defined, and hence the effect of each individual fracture on fluid flow and solute transport can be accounted explicitly. In comparison to the single-fracture model, the fracture-network model, and the pseudo-fracture model, the TSDFC model is more effective for a systematic investigation of the acidization process in fractured carbonate rock masses.

This paper is organized as follows. In Section 2, the mathematical model is presented, to describe the fluid flow, solute transport, and chemical reaction in both the matrix and the fracture system. In Section 3, a detailed numerical solution method is given, which discretizes the physical domain with Delaunay triangulation and discretizes the governing equations with the finite volume method. In Section 4 we compare the simulation results obtained from a degenerate model with a previous computational study to verify our work. In Section 5, the 2-D simulation results of the reactive flow in fractured carbonate media, with simple or complex fracture networks, under linear or radial flow conditions, are presented. The