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A Generalized Numerical Approach for Modeling Multiphase Flow and Transport in Fractured Porous Media

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Abstract. A physically based numerical approach is presented for modeling multiphase flow and transport processes in fractured rock. In particular, a general framework model is discussed for dealing with fracture-matrix interactions, which is applicable to both continuum and discrete fracture conceptualization. The numerical modeling approach is based on a general multiple-continuum concept, suitable for modeling any types of fractured reservoirs, including double-, triple-, and other multiple-continuum conceptual models. In addition, a new, physically correct numerical scheme is discussed to calculate multiphase flow between fractures and the matrix, using continuity of capillary pressure at the fracture-matrix interface. The proposed general modeling methodology is verified in special cases using analytical solutions and laboratory experimental data, and demonstrated for its application in modeling flow through fractured vuggy reservoirs.

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1 Introduction

Since the 1960s, significant progress has been made in mathematical modeling of flow and transport processes in fractured rock. Research efforts, driven by the increasing need to develop petroleum and geothermal energy in reservoirs, other natural underground resources, and to resolve concerns of subsurface contamination, have developed many numerical modeling approaches and techniques (Barenblatt et al., 1960; Warren

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and Root, 1963; Kazemi, 1969; Pruess and Narasimhan, 1985). Mathematical modeling approaches developed in the past few decades in general rely on continuum approaches and involve developing conceptual models, incorporating the geometrical information of a given fracture-matrix system, setting up mass and energy conservation equations for fracture-matrix domains, and then solving discrete nonlinear algebraic equations. Most computational effort is consumed in solving the governing equations that couple multiphase fluid flow with other physical processes either analytically or numerically. The key issue for simulating flow in fractured rock, however, is how to handle facture-matrix interaction under different conditions (involving multiple phase flow). This is because the fracture-matrix interaction distinguishes the flow through fractured porous media from the flow through homogeneous or heterogeneous single-porosity porous media.

To model fracture-matrix interaction during flow in fractured porous media, investigators have developed and applied many different conceptual models and modeling approaches (e.g., Berkowitz, 2002; Neuman; 2005). In modeling multiphase flow and transport, and heat transfer in fractured porous media, the most critical issue is how to handle inter-"flow" or interaction of mass and thermal energy at fracture-matrix interfaces under multiphase and non-isothermal condition. Commonly used mathematical methods for dealing with fracture-matrix interaction include:

- an explicit discrete-fracture and matrix model (e.g., Snow, 1969; Stothoff, 2000),
- the dual-continuum method, including double- and multi-porosity, dual-permeability, or the more general "multiple interacting continua" (MINC) method (e.g., Barenblatt et al., 1960; Warren and Root, 1963; Kazemi, 1969; Pruess and Narasimhan, 1985; Wu and Pruess, 1988),
- the effective-continuum method (ECM) (e.g., Wu, 2000a).

The explicit discrete-fracture approach is, in principle, a more rigorous model. However, the application of this method to field studies is currently limited because of the computational intensity involved as well as the lack of detailed knowledge of fracture and matrix geometric properties and their spatial distributions at a given subsurface site. On the other hand, the dual-continuum method is conceptually simpler and computationally much less demanding than the discrete-fracture approach, and is able to handle fracture-matrix interaction more easily than the discrete-fracture model. For these reasons, the dual-continuum approach has been used as the main approach for modeling fluid flow, heat transfer, and chemical transport through fractured reservoirs (e.g., Wu et al., 1999 and 2007).

Dual-continuum approaches, as discussed in this paper, include the classical double-porosity model (Barenblatt et al., 1960; Warren and Root, 1963), the dual-permeability concept, and the more rigorous dual-continuum generalization of the MINC (Pruess and Narasimhan, 1985) for modeling flow in fractured porous media. In the double-porosity model, a flow domain is composed of matrix blocks with low permeability, embedded in a network of interconnected fractures. Global flow and transport in the formation occur only through the fracture system, conceptualized as an effective continuum. This