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Mathematics and Computers in Simulation 81 (2011) 2270–2281

MATHEMATICS AND COMPUTERS IN SIMULATION

www.elsevier.com/locate/matcom

Original article

Three-dimensional numerical simulation of single-phase transient compressible flows and well-tests in fractured formations

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Received 15 November 2009; received in revised form 8 June 2010; accepted 8 December 2010
Available online 21 December 2010

Abstract

A general three-dimensional numerical model for single phase, slightly compressible flow through fractured porous media is described. It is based on a discrete fracture representation. Three sets of applications are presented. In the first one, pressure drawdown well tests in closed oil reservoirs are simulated for complex model situations where the well intercepts a random fracture network with various fracture densities and conductivities. Then, the hydrodynamic response of a fractured aquifer is investigated by simulating on the field-scale single- or two-well pumping tests in the Poitiers Hydrological Experimental Site. Finally, a complete field-scale simulation of the production history in an oil reservoir with multiple wells is presented.

Keywords: Porous medium; Fracture; Reservoir; Well flow

1. Introduction

This work addresses single phase, slightly compressible flow through fractured porous media. A very general, three-dimensional numerical model based on a discrete fracture representation is proposed, together with applications involving a single or multiple interacting wells.

Due to the specific transport properties of fractures, the flow through a naturally fractured porous medium differs drastically from that in a conventional porous medium. The key feature is that the porous matrix provides the main storage for the fluids while transport takes place mainly through the fracture system. Furthermore, matrix/fracture flow interactions govern many of the medium transport properties. Because of the complexity and diversity of most natural fracture systems, the determination of fractured porous media transport properties remains an open issue of great practical importance. For instance, the present numerical tool can be applied for the interpretation of well test data, in order to quantify the characteristics of a reservoir, or conversely, to optimise the design of a producing well, given the reservoir characteristics.

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doi:10.1016/j.matcom.2010.12.014

Most existing models of transient compressible flow through fractured porous media are based on the concept of double-porosity media [2,18,8,14,10]. A discrete approach allows a more detailed description of the matrix/fracture flow interaction accounting for the flow behavior in individual elements of the medium, but it has been applied so far only to regular system of fractures [16,20,5,21,15]. We presented in [4] an extension to unsteady compressible flow of the numerical models of [12,3], which make use of a full three-dimensional description of random discrete fracture systems.

Its main features are recalled here, as well as results of single-well tests simulations in medium-sized systems (hundreds of fractures), focused on the well response. Then, new applications on a much larger scale (thousands of fractures) are presented, involving many wells which can be simultaneously producing or simply observing. Attention is extended to the transient complex three-dimensional flow field in the fractured aquifer or reservoir. For instance, the possible disturbing effects of supposedly passive wells are demonstrated.

2. Governing equations

The fractured porous medium can be represented as an arbitrary, generally random, set of fractures embedded into a solid porous matrix. At the large scale, each fracture can be viewed as a vanishingly thin layer, with singular transport properties. For instance, a steep pressure gradient may exist across a poorly conducting fracture, which results in an apparent pressure jump at the macroscopic scale. In addition, the typical time for pressure variations in transient flows is quite different in the matrix and in the fractures. The discrete fracture model used in the present work explicitly accounts for these features. Therefore, it allows detailed investigations of transitory flow regimes, and of the influence of the well intersections with the fracture network.

2.1. Flow equations

Consider a porous matrix with a bulk permeability K_m $[L^2]$ which may vary with space. Darcy law for the local seepage velocity $\boldsymbol{v}$ and the mass conservation for slightly compressible flow can be written in the matrix as

$$\boldsymbol{v} = -\frac{K_m}{\mu}\nabla P \quad (a), \qquad \epsilon_m C_m \frac{\partial P}{\partial t} + \nabla \cdot \boldsymbol{v} = \delta_w J_w \quad (b) \tag{1}$$

where μ is the viscosity, P is the pressure, ϵ_m and C_m are the matrix porosity and total compressibility. J_w $[L^2T^{-1}]$ represents the exchanges with the well, at a location given by the Dirac function δ_w $[L^{-2}]$. On this scale of description, the well appears as a line without thickness. If $\epsilon_m C_m$ is constant, a matrix pressure diffusivity D_m can be defined and (1) can be written as a difusion equation for the pressure

$$\frac{\partial P}{\partial t} - \nabla \cdot (D_m \nabla P) = \frac{\delta_w J_w}{\epsilon_m C_m}, \qquad D_m = \frac{K_m}{\mu \epsilon_m C_m} \tag{2}$$

We assume that the hydraulic properties of a fracture can be characterized by two effective coefficients, namely a conductivity $\sigma[L^3]$ and a cross resistance $\omega[L^{-1}]$ (see [3]), which relate the in-plane the flow rate $\boldsymbol{j}$ to the surface pressure gradient $\nabla_s P$ and the seepage velocity $\boldsymbol{v}_\perp$ of the net flow crossing the fracture to the pressure drop $[P]$ across it by

$$\boldsymbol{j} = -\frac{\sigma}{\mu}\nabla_s P \quad (a), \qquad \boldsymbol{v}_\perp = -\frac{1}{\mu\omega}[P] \quad (b). \tag{3}$$

For illustration, the fracture can be viewed as a plane channel of aperture b, filled with a porous material with permeability K_f, porosity ϵ_f and total compressibility C_f. Then, σ and ω are given by $\sigma = bK_f$ and $\omega = b/K_f$. A non zero resistance ω may exist even for totally open channels, if their walls are partially clogged by a deposited chemical [13]. Note that equations similar to (3) for the fracture hydraulic properties have been obtained by [7] by an upscaling procedure.

The continuity equation for the flow through a fracture reads as

$$b\epsilon_f C_f \frac{\partial P}{\partial t} + \nabla_s \cdot \boldsymbol{j} = (\boldsymbol{v}^- - \boldsymbol{v}^+) \cdot \boldsymbol{n} + b\delta_w J_w \tag{4}$$