SPE 122612

Simulation of Multiphase Non-Darcy Flow in Porous and Fractured Media

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This paper was prepared for presentation at the 2009 SPE Annual Technical Conference and Exhibition held in New Orleans, Louisiana, USA, 4–7 October 2009.

Abstract

A Buckley and Leverett type analytical solution is derived for non-Darcy displacement of immiscible fluids in porous media, in which non-Darcy flow is described using the general model proposed by Barree and Conway. Recent laboratory studies and analyses have shown that the Barree and Conway model is able to describe the entire range of relationships between rate and potential gradient from low- to high-flow rates through porous media, including those in transitional zones. We also present a general mathematical and numerical model for incorporating the Barree and Conway model to simulate multiphase non-Darcy flow in porous and fractured media, while flow in fractured rock is handled using a general multi-continuum approach. The numerical solution of the proposed multiphase, non-Darcy flow model is based on a discretization scheme using an unstructured grid with regular or irregular meshes for multi-dimensional simulation. The final discretized nonlinear equations are handled fully implicitly with the Newton iteration. As an application example, we use the analytical solution to verify the numerical solution for and to obtain some insight into one-dimensional non-Darcy displacement of two immiscible fluids according to the Barree and Conway model. Overall, this work provides an improved platform for modeling multiphase non-Darcy flow in oil and gas reservoirs, including complex fractured systems such as shale gas reservoirs.

1. Introduction

Darcy's Law has been used exclusively in studies of porous-medium flow in reservoirs, however, there is considerable evidence that high-velocity non-Darcy flow occurs in many subsurface systems, such as in the flow near wells of oil or gas production, groundwater pumping, and liquid waste injection. Darcy's law, describing a linear relationship between volumetric flow rate (Darcy velocity) and pressure (or potential) gradient, has been the fundamental principle in analyzing flow processes in porous media. Any deviation from this linear relation may be defined as non-Darcy flow. In this paper, our concern is only with the non-Darcy flow behavior caused by high flow velocities. Effects of non-Darcy or high-velocity flow regimes in porous media have been observed and investigated for decades (e.g., Tek et al., 1962; Scheidegger, 1972; Katz and Lee, 1990; Wu, 2002). Most studies performed on non-Darcy flow in porous media in the early time have focused mainly on single-phase-flow conditions in petroleum engineering (Tek et al., 1962; Swift and Kiel, 1962; Lee et al. 1987). Some investigations have been conducted for non-Darcy flow in fractured reservoirs (Skjetne et al., 1999) and for non-Darcy flow into highly permeable fractured wells (e.g., Guppy et al., 1981, 1982). Other studies have concentrated on finding and validating correlations of non-Darcy flow coefficients (e.g., Liu et al., 1995).

In analyzing non-Darcy flow through porous media, the *Forchheimer* equation (1901) has been exclusively used to describe non-Darcy porous media flow, and has been extended to multiphase flow conditions (Evans et al., 1987; Evans and Evans, 1988; Liu et al., 1995; Wu, 2001 and 2002). Recent laboratory studies and analyses have shown that the Barree and Conway model is able to describe the entire range of relationships between flow rate and potential gradient from low- to high-flow rates through porous media, including those in transitional zones (Barree and Conway, 2004 and 2007; Lopez, 2007). In this paper, we derive a Buckley and Leverett type analytical solution for one-dimensional non-Darcy displacement of immiscible fluids in porous media using the Barree and Conway model. We also present a general numerical model for incorporating the Barree and Conway model to simulate multiphase non-Darcy flow in porous and fractured media.

This paper represents a continual study of our previous investigation of single-phase non-Darcy flow in reservoirs according to the Barree and Conway model (Lai et al. 2009). The objective of this study is to develop a mathematical method for quantitative analysis of multiphase non-Darcy flow through heterogeneous porous and fractured rocks using the Barree and Conway's model. The numerical solution of the proposed mathematical model is based on a discretization scheme using an unstructured grid with regular or irregular meshes for multi-dimensional simulation. The final discretized nonlinear equations are handled fully implicitly with the Newton iteration. The flow in fractured rock is handled using a general multi-continuum approach. As an application example, we use the analytical solution to verify the numerical solution for and to obtain some