International Journal of Heat and Mass Transfer 96 (2016) 396–405

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Multiscale mixed finite element, discrete fracture–vug model for fluid flow in fractured vuggy porous media

Na Zhang, Jun Yao *, Shifeng Xue, Zhaoqin Huang

China University of Petroleum (East China), Qingdao City, Shandong Province 266555, China

ARTICLE INFO

Article history:
Received 23 May 2015
Received in revised form 24 November 2015
Accepted 24 November 2015
Available online 4 February 2016

Keywords:
Multiscale mixed finite element method
Discrete fracture–vug model
Numerical simulation

ABSTRACT

Numerical simulation in naturally fractured-vuggy media is challenging because of the coexistence of porous media, fractures and vugs on multiple scales that need to be coupled. We present a new approach to reservoir simulation, based on the discrete fracture–vug network (DFVN) model, which gives accurate resolution of both large-scale and fine-scale flow patterns.

In this work, we use a multiscale mixed finite element method (MsMFEM) for fluid flow in fractured-vuggy media using the discrete fracture–vug model. By combining MsMFEM with the discrete fracture–vug model, we aim towards a numerical scheme that facilitates fractured vuggy reservoir simulation without upscaling. MsMFEM uses a standard Darcy model to approximate the pressure and velocity on a coarse grid, whereas fine scale effects are captured through basis functions constructed by solving local flow problems using the discrete fracture–vug model. The accuracy and the robustness of MsMFEM are shown through several examples. In the first example, we consider Beavers–Joseph model and then compare the analytic solution. We use the MsMFEM in more complex models. The results indicate that the MsMFEM is a promising path toward direct simulation of highly resolution geomodels.

1. Introduction

Numerical simulation of fluid flow through fractured vuggy porous media remains to be very challenging. Naturally fractured vuggy systems contains not only porous media and multiple length-scale fractures, but also the vugs that vary in size from centimeters to meters in diameter [1]. In addition, the effect of the heterogeneity of the porous media and the random distribution of the fractures and vugs is significant [2,3].

Fluid flow in fractured vuggy media are affected by heterogeneities in a wide range of scales. Therefore, it is difficult to resolve numerically all of the scales. Typically, upscaled or multiscale methods are employed for such systems [4–7]. The main idea of upscaling methods is to form coarse-scale equations with a analytical form.

As an alternative method, numerical upscaling calculation based on accurate geologic models has received much attention recently. While using numerical upscaling calculation methods to evaluate the permeability of porous materials, two important steps should be mentioned. Modeling the fluid flow through fractured vuggy porous media on fine scale is the first step on which the main difficulty is the co-existence of porous flow and free-flow regions. And then, how to incorporate this fine scale data into coarse scale flow properties is the key step. Neal et al. [8] are the pioneers of the related research; they studied the impact of spherical vugs on the permeability in homogeneous isotropic porous media. In their study, creeping Navier–Stokes equation was employed in the spherical cavity, and the Darcy equation was used to describe the flow in porous medium. Applying the formula for the pressure field near a single spherical cavity, they developed an analytical formula for permeability of a vuggy porous medium.

These upscaling methods have proved quite successful [9,10]. However, it is not possible to have a priori estimates of the errors that are present when complex flow processes are investigated using coarse models constructed via simplified settings. In multiscale methods, the fine-scale information is carried throughout the simulation. The coarse-scale equations are generally not easy to treat analytically, but rather formed and solved numerically. A number of multiscale numerical methods have been presented, such as heterogeneous multiscale method (HMM) [6], multiscale finite element method (MsFEM) [11] and variational multiscale method [7,12]. Multiscale methods have proved to be capable of handling industry-standard complexity with respect to both grid representation and flow physics [13–15]. Here, we study multiscale mixed finite element method (MsMFEM) for fluid flow in

* Corresponding author.
E-mail address: rcogfr_upc@126.com (J. Yao).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.11.090
0017-9310/

fractured vuggy media. The main idea of this method is to construct multiscale basis functions which capture the fine scale features and the fine scale information is then brought to the large scales through the coupling of the global stiffness matrix.

MsFEM is first introduced by Hou and Wu [11]. This method is based on the construction of multiscale finite element basis functions that are adapted to the local property of the differential operator, and was introduced as a tool to solve elliptic partial differential equations with multiscale solutions. This approach has proved to be more robust and accurate than upscaling methods for Darcy flow [16] and it could offer fine-scale resolution. MsFEM has been modified and applied to simulate two-phase flow in porous media [17–19]. Multiscale finite element methods using global information are introduced by Aarnes [20]. The main idea of these approaches is to use some simplified surrogate models to extract important information about non-local multiscale behaviour of physical processes. MsFEMs using global information have been previously used in the work of Efendiev et al. [21]. They used single-phase flow information for accurate upscaling of two-phase flow and transport. Although, MsFEM generates solutions that reflect the fine-scale characteristics of the elliptic coefficients, these solutions are not locally mass conserving. Thus, Chen and Hou introduced multiscale mixed finite element method (MsMFEM), which is locally mass conserving on the coarse grid. Moreover, MsMFEM is suitable for problems with complex flow physics and irregular grids. Gulbransen et al. [22] used multiscale mixed finite-element method for simulating the single-phase flow of vuggy media and constructed different flow models on the coarse and the fine scale. To date, however, MsMFEM has not been applied to simulate multiphase flow in naturally fractured vuggy media using a discrete-fracture–vug model.

Typical models for the representation of naturally fractured vuggy systems generally rely on the triple-continuum models. In recent years, there have been some important developments in numerical methods of flow in fractured vuggy porous media. Most of the existing research and numerical simulator are based on triple continuum model and the extended model. This model treats matrix system, fracture system and vug system as porous media, coupled by crossflow function. The triple-continuum models is widely used because of their simplicity, but research results have indicated that it is only valid for the formation with highly developed fracture and cannot be used for the numerical simulation of multiphase flow in disconnected fractured-vuggy media and mixed-wet fractured-vuggy media. Although these models are very efficient, they fail to capture this important property of such systems [23]. Simultaneously, great troubles exist in the determination of crossflow function of two-phase flow. As an alternative continuum approach, the equivalent continuum models represent fractures, vugs and matrix as a single effective continuum based on the concept of effective permeability tensor and porosity. The equivalent continuum models have been used for modeling fractured rock flow, because the main advantages of the model are its simplicity and high computational efficiency. However, the equivalent continuum models have not yet been applied in fractured vuggy porous media because of the difficulty on the parameter estimates for effective porosity and permeability. The strength of the continuum approach lies in its simplicity. However, the continuum models cannot describe the co-existence of porous and free-flow patterns which is the distinguishing feature of fractured vuggy porous media, because they over regularize and simplify the geometry of the fractures and vugs systems. Fractured vuggy rock mass are composed of blocks separated by discontinuities, and therefore discontinuum models may be natural and attractive approach to representing these systems in which the complex flow patterns exist. Thus, Yao et al. introduced the discrete fracture vug network model, which is an extension of classic discrete fracture network for fractured vuggy porous media.

The discrete fracture network model was first introduced for single phase flow by Noorishad and Mehran [24]. The DFN model is based on the concept of cross-flow equilibrium between the fluids in the fractured node and the matrix node next to the fracture. Baca et al. [25] use one-dimensional entities to represent fractures to simulate single phase flow in fractured porous media. Many authors have studied the fractured media using DFN model. The work of Kim and Deo [26,27] is based on the finite element method and the superposition principle to couple the two media. Their proposed model is similar in principle to DFN model. Karimi-Fard [26] and Huang et al. [28] presented extensions of the work of Baca et al. for two-phase flow. They modeled the fractures and the matrix in a two-dimensional configuration .The porous media and fractures were coupled using a superposition approach. This entails discretizing the matrix and fractures separately and then adding their contributions to obtain the overall flow equations. Moreover, other numerical methods, except the finite element method (FEM), have been discussed. Yao et al. [29] proposed DFVN model, which adds the isolated macro vugs into the fractured media. The combined free/porous flow is the main characteristic of DFVN model. Based on our previous research, discrete fracture vug model can be adopted to study fractured vuggy porous media. One of our purposes in this paper is to use the discrete fracture vug model for multiscale simulations of fractured systems.

Our purpose in this paper is to present a MsMFEM for multiphysics simulation of fluid flow in naturally fractured vuggy media. The MsMFEM combines Darcy's law and mass conservation to approximate pressure and velocity on a coarse grid. Fine-scale effects of fractured porous media are captured through basis functions which are determined by solving local Darcy–Brinkman flow problems numerically using DFVN model on the underlying fine-scale geocellular grids. For fractured vuggy media with strong non-local effects, some type of global information can be built into the basis functions. In this paper, we discuss the use of global information in multiscale methods. The main idea of the method is to use the limited global fine-scale solution at initial time to determine the boundary conditions of the basis functions. The use of limited global information allows us to capture the fine scale features more accurately compared to the multiscale mixed finite element methods that use only local information to construct the basis functions.

This paper is organized in the following way. In the next section the fluid flow mathematical model is briefly introduced. In Section 3, we present the details of multiscale mixed finite element method. The numerical formulas of fluid flow model based on discrete fracture–vug model are also demonstrated. Numerical examples are provided in Section 4 to demonstrate the validly and accuracy of the MsMFEM for incompressible flows. All the results obtained are thoroughly analyzed and compared with MsMFEM method and other available results wherever possible. Finally, in Section 5, some important conclusions are derived.

2. Mathematical models

As observed in carbonate formation, three porosity types (matrix, fractures, and vugs) are typically presented in naturally fractured vuggy porous media. These fractures and vugs distribute irregularly and vary in size, from microscopic to macroscopic. Several continuum conceptual models have been proposed to study the flow behavior through such media in [11–13]. In the DFVN conceptual model, the fractures and vugs are embedded in porous rock, and the isolated vugs are connected via discrete fracture