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Multiscale mass transfer coupling of triple-continuum and discrete fractures for flow simulation in fractured vuggy porous media

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ABSTRACT

Fractured vuggy porous media continue to challenge the flow simulation research involving mass and/or heat transfer processes. Here, we report a coupled multiscale and multi-continuum approach developed to improve the modeling of multiphase flow through fractured vuggy porous media involving multi-continuum mass transfers. Multiple levels of fractures can be not only modeled as different superimposed continua but also embodied as discrete fracture networks based on their geometrical characteristics. Different configurations of vuggy existence can also be handled by a continuum and/or their discrete representations. We develop a systematic coupling using Multiscale Finite Element Method (MsFEM) as a framework for coarsening and refinement. MsFEM is used to capture subgrid scale heterogeneities and interactions through multiscale basis functions calculated based on the multi-continuum background. Unstructured mesh is applied to model discrete fractures in arbitrary directions and discrete vugs with complex geometries. This paper presents a significant advancement in terms of elevating the limitations of the multi-continuum models in handling complex fracture and/or vug geometry and extending the model reduction capability of MsFEM. Several numerical examples are carried out to demonstrate the capability of the proposed coupling method.

1. Introduction

Fractured vuggy porous media are naturally existing, such as the carbonate formations bearing essential natural resources (e.g. groundwater and hydrocarbon) [1–3], and have attracted great scientific interests [4–12]. The modeling and simulating of multiphase flow through fractured vuggy porous media involves mass transfer among different continua of distinct scales and remains to be very challenging. There are not only fractures at multiple length-scales but also vugs whose sizes vary from centimeters to meters presenting in naturally fractured vuggy porous system [13,14]. Fractures in subsurface formations are often distributed because of their geotectonic origins and could be disconnected or connected forming network(s) [15]. On the other hand, vugs are formed due to their diagenesis process and could be isolated or connected with fractures [16]. Combining with the already heterogeneous porous matrix, the level of complexity is significant in terms of the characteristics of fractured vuggy porous media [17,18].

A fine-scale simulation model is perhaps the first attempt to understand the flow dynamics and mass transfers happening in such media. In general, unstructured gridding are required to describe the directions of fractures and the geometries of vugs and their connections. Multiphase flow equations are then discretized on the unstructured grids and solved using finite element, finite volume method and their coupling. We do note that the emerging isogeometric analysis invented by Hughes [19] offers the flexibility to use (Non-uniform rational Basis spline) NURBS as the calculation mesh for finite element analysis and may offer a paradigm shift in flow simulation through porous media.

Those mentioned multiscale heterogeneities and complexities in fractured vuggy system make it very difficult and practically impossible to resolve numerically all of the scales using a fine-scale simulation model. The co-existence of free flow and porous media flow further exacerbates the situation [20]. Therefore, some types of model order reduction are necessary to facilitate flow simulation investigation in such media. Typical model reduction method involves the upscaling approach [21,22]. Traditional upscaling approach is in general a preprocessing workflow toward simulation. Effective properties, such as permeability, is precomputed in each coarse block that is comprised of an agglomeration of fine gird blocks, to somehow incorporate fine scale information

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into coarse scale mass transfer properties. Neale et al. (1973) [23] pioneered to develop an analytical formula for vuggy porous media permeability by studying the impact of spherical vugs on the permeability of homogeneous isotropic porous media containing those vugs. The flow-based upscaling methods have been quite successful, but it is not sufficient in the sense that it cannot have a priori error estimate for complex multiphase flow processes using coarse grid blocks constructed via simplified setting and it cannot properly resolve the multiple interacted media within each coarse grid block, such as matrix, fracture and vug to model the mass transfer process among them.

The concept of multi-continuum model comes into place by considering multiple interconnected parallel systems that distribute all over the domain at any point in the flow field. This is a very insightful and reasonable simplification for naturally existed rock media. And indeed, the first multi-continuum model – dual porosity model (DPM) is proposed by Barenblatt for flow through naturally fissured rock [24]. In DPM, matrix and fracture are considered as two porosity types co-existing at the same spatial location. Mass transfers between those two porosity types are coupled through a transfer function, which is often obtained under steady state or pseudo steady state assumptions [25,26]. Following the introduction of DPM, subsequent extensions and developments have been carried out in the past half century for different media including fractured vuggy porous media. Recently, Yan et al. [27] generalized this approach by proposing a general multi-porosity model, which can handle any number of porosity types (continua) with arbitrary connection among different porosity types (continua), and applied to unconventional reservoir with multiple level of fractures (from micro fracture to natural fracture and then to hydraulic fractures). For fractured vuggy porous media, a number of literatures have made some important developments in numerical models based on the multi-continuum concept [5,10,18,28,29]. In common, their approaches use a typical triple-continuum model. Beyond the standard dual porosity model, a third porosity type, or continuum, is added to represent the vug system, coupled using the corresponding inter-continuum transfer functions.

Since their computational efficiency, these triple-continuum models have been widely adopted in the reservoir simulation and ground water modeling communities mainly because of their simplicity. However, research has indicated a number of limitations, which are mainly attributed to the assumptions that the continua are connected throughout the entire simulation domain. The continuum model represents heterogeneity within a coarse block by a tensor, often failing to qualify the local features to an acceptable accuracy. Indeed, because of this assumption, trip-continuum models may only be valid for the reservoirs with highly developed fractures and/or vugs and may not be used for multiphase flow simulation for porous media with disconnected fractures and/or vugs. In other words, the limitations of multi-continuum model in simulating multiphase flow through fractured vuggy reservoir is because the fracture and vug systems are all global, no matter how many levels of continua used. For those fractures and/or vugs whose effects are local because of separation by discontinuities, then "discontinuum" may therefore be naturally necessary and attractive. For instance, the Discrete Fracture model (DFM) is a typical "discontinuum" approach, which is based on cross-flow equilibrium between the fluids in the fracture node and the surrounding matrix node [30].

Following the introduction of DFM, many authors have studied the fractured media using DFM [31–36]. DFM considers the heterogeneity and discontinuity characteristics of fractured media, which can describe the flow characteristics accurately. In DFM, the dimensionality of the fractures is reduced from n to $n-1$. This reduction greatly decreases the computational time. It is suitable for the fractured media with a number of discrete fractures. Discrete Fracture-Vug model (DFVM) is also recently developed [16]. The combined free/porous flow is the main characteristic of DFVM. Based on the previous research, DFM is able to describe the flow characteristics of the models with fractures quite accurately. The main disadvantage is that it is not suitable for handling small-scale fractures, mostly because of the scale discrepancy. In addition, the spatial distributions of small-scale fractures are unknown in general.

To have the merits of multi-continuum and discontinuum approaches, the motivation of coupling both is intuitively natural. Chai et al. [37,38] recently embedded discrete fractures into multi-porosity models. Using non-neighbor connections, the effects of discrete fractures can be preserved in the model. On the other hand, in order to capture different scale flow features, a variety of approaches combining multiscale methods and fracture models have been proposed for fracture reservoirs [39–43]. In these literatures, multiscale methods can carry fine-scale information throughout the simulation and allow large-scale fractures with an arbitrary orientation to be included into models. However, they are all based on two discrete-fracture models (Unstructured discrete-fracture model and Embedded discrete-fracture model), which are intended to explicitly represent discrete fracture networks. The coupling with multiple continua is not considered. In a recent paper [39], we proposed a new multiscale formulation that embodies discrete fracture network and couples with dual-continuum model for simulating single component gas transport in shale. Discrete fracture model is used to resolve fractures and dual-continuum is used for representing inorganic and organic matters.

In this paper, we develop a multiscale finite element formulation that couples matrix, global fracture, discrete fractures and vugs systems. The numerical scheme combines multi-continuum model and discrete fracture model to approximate pressure and saturation on fine and coarse scale. Fine-scale features of finer scale grid are captured through basis functions that are determined by solving flow problems using multi-continuum model. In this paper, we discuss the different cases to compare the accuracy of the proposed method.

The rest of this paper is organized as follows. In Section 2, we provide the problem formulations for multiphase flow through fractured vuggy porous media. We then derive the numerical approximation for flow potential equation and saturation equation separately. In Section 3, we discuss the fine scale discretization for the flow potential equation. The details of multiscale method and the coarse-grid system formulation for flow potential are described in Section 4. In Section 5, we provide an approach for saturation approximation. We then demonstrate numerical examples in Section 6. Finally, in Section 7, we conclude and summarize the work.

2. Triple-continuum model formulation

Here we consider three continua types, namely matrix, fracture, and vug, which is in accordance with observations in fractured vuggy porous media. In this triple-continuum model setup, we assume fracture and vug systems are global. It should be noted that, matrix is global by default because of the nature of the media of interest. To ease the understanding of our new method in this paper, a few concepts are firstly introduced as follows:

- Inter-continuum transfer: the mass transfers between two different continua. For example, the intra-continuum transfer between the matrix continuum and the fracture continuum represents the communication between these two continua that are superimposed at the same spatial gridding location. Similar facts hold for the intra-continuum transfer between the matrix continuum and the vug continuum, and between the vug continuum and the fracture continuum.