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Improved skeleton extraction method considering surface feature of natural micro fractures in unconventional shale/tight reservoirs

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ABSTRACT

Massive micro fractures (MFs) developed in the ultra-tight formations (such as shale/tight reservoirs), which provide preferential channels for the fluids flow. Accurate characterization of such pore-fracture systems and suitable pore network models are the fundamentals of pore structure characterization and micro scale flow simulation. Conventional medial axis (MA) skeleton extraction method cannot preserve the fracture surface feature and connectivity information, which is not suitable for accurate pore scale simulation for these porous media with MFs.

In this paper, a new skeleton model was proposed to distinguish MFs from pore space via extraction of surface points set of MFs. In the procedure of points set extraction, we improved the classic "MA based" shrink method to "medial surface (MS) based" method for the MFs characterization through introducing a new set of skeleton points (i.e., surface points and edge points of the micro fractures). The former describes their apertures and the latter is used for collecting connectivity information and determining the extension ranges of the MFs. Comparison of connectivity index, fracture length, Euclidean distance showed enhanced effectiveness and accuracy of the proposed method. The proposed method was applied in four ideal models and one field shale core sample. Results show that the proposed skeleton model can show more comprehensible forms of the real connected junction instead of the conventional ideal model. The extracted skeleton can also satisfy demands of the traditional skeleton extraction model and preserve the topology of the original pore-fracture space. This work proposed a more accurate method for pore-scale modeling in cores with natural MFs, and potentially applicable for pore scale flow simulations for tight/shale reservoirs.

1. Introduction

Micro fractures (MFs) are widely existed in global oil/gas reservoirs, especially in unconventional shale oil/gas reservoirs, coal seams, and tight sandstones, etc (Guo et al., 2015; Jiang et al., 2007; Peng et al., 2017; Prodanović et al., 2008; Wang et al., 2015a). These MFs have higher conductivity compared with the matrix and serve as the preferential channels for the fluids flow (Prodanović et al., 2008; Karpyn and Piri, 2007; Roubinet et al., 2009). Investigation on the fluid transport mechanisms in the MFs is of great importance for optimizing the numerical simulation of macro fractured reservoirs (Karpyn and Piri, 2007; Williamsstroud et al., 2013; Hughes and Blunt, 2001; Madadi and Sahimi, 2003). Currently, multiple methods have been proposed to simulate pore-scale fluid flow, such as lattice boltzmann method (LBM) (Madadi and Sahimi, 2003; Sukop and Cunningham, 2015) and level set method (Prodanović et al., 2008; Han et al., 2003), which can simulate the micro fracture space directly. These methods are relatively accurate, however, the computation cost is also huge. Some scholars also simplified the fracture as a traditional plate model or a regular network model (Karpyn and Piri, 2007; Hughes and Blunt, 2001). By this method, the calculation speed can be improved. However, due to the over-weakening of the fracture structure, significant calculation errors are brought in (Peng et al., 2017). Therefore, how to accurately identify MFs and reasonably construct the skeleton models containing MFs is continuously concerned by researchers.

As a new research method, the rapidly developed high resolution imaging technology can transform pore space into digital images, which starts the simulation stage based on the digital core technology (Karpyn and Piri, 2007; Cnudde and Boone, 2013; Zhao et al., 2007; Blunt et al., 2013; Bultreys et al., 2016; Wildenschild and Sheppard, 2013). Pore skeleton networks were used in many fields to model porous media, for example in the evaluation of cellular materials (Viot et al., 2008;

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Fischer et al., 2009) and in the examination of rocks and sands (Wildenschild and Sheppard, 2013; Xu et al., 2017; Homberg et al., 2013). After obtaining the image data by scanning the core sample, some structural parameters of pores and fractures can be simply obtained by some general image processing software. However, this method cannot realize batch processing of core data (Wang et al., 2015b). In recent years, a new method combining morphological operation with digital core technic has been gradually utilized in the study of pore structure characterization. This method can keep the topology of pore space, which can accurately characterize the pore structure. For ordinary pore space, Lee et al. (1994) put forward the medial axis theory to represent the topological structure of pore space and obtained important parameters such as coordination number, pore radius, etc. Later, Lindquist et al. (2000) further developed the pore space shrinking algorithm, which builds the medial axis skeleton model of pore space by eliminating those simple points having no contribution to the pore structure characteristics. Jiang et al. (2007) put forward the planar skeleton, and made a further attempt to better describe the flat structure in pore space. At the same time, multiple skeleton extraction optimization algorithms have been proposed (Jiang et al., 2007; Homberg et al., 2013; Dhanalakshmi et al., 2016; Lee et al., 2013; Delerue and Perrier, 2002; Sok et al., 2002; Arand and Hesser, 2017; Dong and Blunt, 2009). At the same time, the pore network model containing pore structure and connectivity information has been proposed, which further promotes the development of pore-scale modeling and flow simulation (Blunt et al., 2013; Bultreys et al., 2016; Dong and Blunt, 2009; Blunt, 2001; Lopez et al., 2003).

The existence of micro fractures (MFs) is one of the main reasons leading to the heterogeneity and multi-scale in pore space. However, few research have been conducted based on the real fracture extension and morphology. Fractal characterization of the fracture network is effective, but it is not suitable for the single fracture in non-network state (Wang et al., 2015a). After comparison, skeleton model has many advantages. It can not only represent the topological structure of complex three-dimensional pore space intuitively, but also can simplify pore structure characterization without changing the topological characteristics of pore space. Also, it can preserve the geometric properties of pore space, such as the geometric center of space. Thus, after fully consideration of the structural differences between MFs and matrix pores, the skeleton model can be used to describe the real morphology of the fractures. The traditional medial axis skeleton model describes the pore flow channels as linear. For pore space with more complex structure, this method is not enough to maintain the topology structure and can cause significant errors in later structure analysis and flow simulation (Riasi et al., 2016).

In this paper, we treated the micro fractures (MFs) as one kind of special pores in the space. On the basis of summarizing the topological structure differences between the MFs and the ordinary pores, a new skeleton extraction algorithm combined with morphological operation theory was proposed, which can be utilized to identify MFs, construct the skeleton model with MFs, and extract the structure characteristics of MFs, such as aperture, inclination angle, and connectivity, etc.

2. Micro fractures in the reservoir formations

The fractures with aperture in the range of 1–100μm are called the micro fractures (MFs), which is often developed in unconventional tight/shale reservoirs (Guo et al., 2015; Wang et al., 2015a; Roubinet et al., 2009). These MFs usually existed in the intergranular and intragranular pores as opening, closing, or filling states (Wilson et al., 2003). The main research objects for fracture flow simulation are based on the MFs as opening, filling, and semi-filled state. Fig. 1 shows the existence of MFs in sedimentary rocks by thermal imaging. From Fig. 1, it can be found that the MFs are widely existed and irregular. Combined with the matrix and vugs, these MFs formed the multi-scale fluid transport network. Especially in the unconventional reservoir rocks, due to poor pore development and connectivity, the MFs with good development and connectivity are the main channels for the oil/gas flow through. This enables research on the pore space characterization and fracture-matrix connectivity for pore-fracture systems to become a hot and tough research topic.

With the rapid development of imaging technology, the three-dimensional structure of the fractures and pores can be clearly displayed in the digital image (Fig. 1). Different from tubular structure of the conventional pores, the spatial structure of MFs shows more complex surface and multi-scale characteristics: (1) The fault geometry of the MFs is distributed as wedge shape and extends along the development direction; (2) The geometry size is a few orders of magnitude larger than the ordinary pores; (3) The MFs and pores are interconnected with each other. And there are many connected micro pore networks around the fractures.

To ensure the topological structure invariance in the skeleton model extraction with MFs, it is not only required to guarantee the tubular flow in the pores and the surface flow in the MFs, but also needed to accurately characterize the channeling phenomenon between pores and MFs. Therefore, different from the ordinary pores in which the skeleton model can be described as network structure using linear combination, the skeleton model containing MFs should represent the coexistence of lines and surfaces. The skeleton line (medial axis) describes the linear flow path in the pore space. The skeleton surface (medial surface) describes the surface features of the MFs. Similar to the linear skeleton in ordinary pore space, medial surface of MFs should be located in the center of the whole micro fracture so that the topological structure can be maintained. Lines and surfaces are interconnected with each other to characterize the complex multi-scale connectivity between MFs and matrix micro pores.

3. Pore-fracture space characterization method

3.1. Treat pore-fracture space as points set

With the development of image acquisition technology such as computed tomography (CT) and focused ion beam scanning electron microscopy (FIB-SEM) (Guo et al., 2015; Bultreys et al., 2016; Wildenschild and Sheppard, 2013), it is becoming more and more convenient to obtain three-dimensional digital images of pore space. Using points set as the basic space element to describe the pore space with MFs, the topological morphology characteristics are not affected by the resolution. By organically combining concepts such as the space dimension, image, direct neighboring domain, etc, we can more clearly illustrate the topological characteristic with line-surface co-existence so that the morphology of pore-fracture system can be more realistically represented. The relationship between space and image has been illustrated in Fig. 2. Therefore, we described the skeleton surfaces and skeleton lines based the topological structure characteristics of the micro fractured pore space. The pore space has been classified into simple points set, medial axis points set, medial surface points set, and edge points set (Fig. 3). Specifically, the simple points are defined as those points which have no effect on the topological structure of the original pore space if being deleted (Lohou and Bertrand, 2007). The medial axis points, the medial surface points, and the edge points compose the space skeleton model of the pore-fracture space. The point sets of the medial axis points characterize the tubular feature and form as the skeleton line. The medial surface point sets and the edge point sets make up the skeleton medial surface. The surface point sets characterize the surface feature of MFs and the edge points represent the boundary between the pores and MFs so that the fracture extension range and connectivity relationship with surrounding matrix pores can be determined.