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Experimental and numerical investigations of permeability in heterogeneous fractured tight porous media

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ABSTRACT

Analyzing gas flow behavior is important for production prediction in heterogeneous fractured shale reservoirs, which is complex due to the presences of nanopores and high-degree heterogeneity in these complex flow network. First, we applied the discrete fracture model to simulate gas pulse-decay experiments in core plugs with different configurations. The effective permeability ratio was proposed to evaluate the effects of heterogeneity, fracture, and vug on the flow behavior. Second, we performed pulse-decay experiments on one intact fractured shale core to examine the effects of pore pressure and effective stress on permeability variations. The measured pressure profiles were history matched by numerical methods to obtain the porosity and permeability of matrix and fracture. The matching degree is evaluated by the Global Matching Error (GME). Our results highlight the positive impact of dense fracture network to improve flow capacities in the tight reservoir: effective permeability of the fractured core with 8 pairs of 1.3-cm connected fractures increases 4.07 times that of the un-fractured core. Vugs might be important as well if they connect adjacent fracture networks, but their own contribution to flow capacity is negligible: effective permeability increases only 1.00 to 1.02 times when the number of vugs increase from 3 to 35. The GME ranges from 0.04% to 0.2% for history matching of the fractured core. Core heterogeneity is exhibited more obviously when gas flows through under low pressure than under high pressure, which can be used to guide the design of pulse-decay experiment properly depending on the purpose. The main contributions of this study are that we constructed the finite-element based numerical model to simulate the pulse-decay experiment, proposed a methodology to upscale core permeability when fractures and vugs are present, and measured porosity and permeability for the matrix and fracture simultaneously in one fractured core over a wide range of pressure and effective stress.

1. Introduction

Shale gas is a major component of natural gas supply around the world. Shale gas production is projected to account for about two-thirds of the total natural gas production in the U.S. by 2040 (EIA, 2017). Fractures, both natural and hydraulic, are important for the development of unconventional shale gas and oil reservoirs, as they provide the fast flow path for fluids moving from the matrix to the wellbore because of their great transport capacity (Gale and Holder, 2011; Cai et al., 2017). Besides, shale reservoirs are highly heterogeneous with permeability from nanodarcy scale in micro-pores to microdarcy scale in macropores (Jin, 2014; Chen, 2016). Therefore, it is essential to quantify and upscale the flow capacity of the fractured shales in terms of the effective permeability. On the other hand, fracture and vugs are important features of some carbonate reservoirs that they present multiple types of fluid flow in the matrix, cavities and fractures (Sun et al., 2018). Understanding transient flow behavior is important in such fractured and vuggy formations to analyze production behaviors of tight gas reservoirs during primary depletion process.

Pulse-decay method to estimate permeability of tight porous media is based on the transient fluid pressure transmission process (Civan et al., 2012; Jia et al., 2018a). Properties of the tested core samples can be obtained by interpreting the pressure data. Based on the initial pressures and the equilibrium pressure, as well as the volume of reservoirs and core bulk volume, porosity can be estimated from the Boyle's law after accounting for the non-linear compressibility factor of the tested fluid. A lower equilibrium pressure indicates a large pore volume. The laboratory determined permeability is the apparent value depending on flow conditions. In tight porous media, slip flow, Knudsen diffusion, and surface diffusion all contribute to the apparent permeability (Javadpour et al., 2007; Fathi et al., 2012; Ning et al., 2015). In contrast, the inherent permeability only depends on the pore structure

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of the porous media (Civan et al., 2012). The pulse-decay system mainly contains three components: the upstream reservoir, core, and downstream reservoirs. Pressure build-up and decline curves can be obtained at the downstream and upstream reservoirs, respectively, after the pulse-decay test.

Previous researchers have derived analytical solutions for the gas pressure pulse-decay process. Brace et al. (1968) first applied the transient pulse-decay experiment to measure the permeability of granite, and they provided one solution assuming no compressive storage in the porous media. The main drawback of the solution by Brace et al. (1968) is that the pore volume of the core sample is assumed to be negligible, therefore, the accuracy of their solution is compromised. Hsieh et al. (1981) provided a comprehensive analytical solution to describe the transient pressure transmission process by introducing the compressive storage effect. Dicker and Smits (1988) further simplified the analytical solution with high accuracy for fast engineering application. Cui et al. (2009) improved the solution taking into account of adsorption/desorption when the flowing fluid is adsorptive gas. In addition to the analytical method, the flow process can be simulated numerically based on the initial and boundary conditions of the system (Lin, 1977). Jia et al. (2018a) presented a study of flow behaviors of multiple types of gas in shale core plugs. In that study, the apparent permeability of the gases and adsorption profile in forms of Gibbs and absolute adsorption (Sudibandriyo et al., 2003) were measured over a wide range of pressure, and the complex relationships between adsorption and permeability were also investigated comprehensively. Jia et al. (2017) conceptually modeled pressure behaviors in heterogeneous core plugs with and without the presence of a fracture, and experimentally explored the core heterogeneity effect on the flow behavior by flowing gas from one direction and the opposite direction.

Exploration of the multiscale, double porosity feature of tight core plugs using gas as flowing fluid in the pulse-decay experiment was started by Ning (1992). Ning (1992) provided analytical solutions for the gas pressure pulse transmission process in homogeneous and fractured cores with open and closed end. They also developed an in-house finite difference simulator to simulate the flow process in ultra-low permeability core plugs. Almost at the same time, Kamath et al. (1992) demonstrated the applicability of estimating properties of matrix and fracture using water as the flowing fluid in conventional fractured core plugs. In recent years, Cronin (2014) developed layered dual permeability model validated by experimental data performed on cement core plugs. Fractures he studied in the simulation can be planar and orthogonal. Bhandari et al. (2015) characterized stress-dependent porosity and permeability of Barnett shale using core plugs with horizontal bedding and vertical bedding by the pulse-decay experiment. They found that the horizontal-bedding core is more permeable than the vertical-bedding core. Preferential flow path was found by observing a double porosity region formed in the pressure curves before reaching final equilibrium, which is suggested to be attributed to the existence of multiscale permeability with more permeable organic-rich matter and less permeable siliceous matter. A problem of characterizing the fracture flow is the inertia effect associated with the turbulent flow, especially under high-pressure gradients. Turbulent flow, in nature, is extremely sensitive to disturbance in boundary and inlet conditions arose during the experimental operations (Meldi et al., 2011). This fact induces the uncertainty of fracture flow that can be hardly avoided that the transient process makes the flow phenomenon more unpredictable. However, the analytical and numerical solutions are deterministic and cannot predict the inherent uncertainty of fracture flow present in real laboratory experiments and the field.

Theoretically, both fracture permeability and porosity decrease as the effective stress increases (Ye and Ghassemi, 2016), corresponding to the fact that natural fracture tends to close as pore fluids are withdrawn from the reservoir. This phenomenon has been identified by several scholars using the conventional method where the fracture permeability is estimated based on the Darcy equation when fluid flows through the fracture with a constant flow rate under steady state. For instance, Jones (1975) showed through experiments that the cubic root of fracture permeability is linearly correlated with the confining pressure. Gangi (1978) derived the function of fracture permeability with effective stress accounting for the distribution patterns of the asperity height. To reduce the effect of turbulent flow in the fracture, the flow rate was always controlled to be very low meaning that the tested pressure gradient was very low. However, only measuring properties under low pressure lessened the significance of the original purpose because gas pressure in most reservoirs is usually thousands of psi especially in deep shale gas reservoirs. Alnoaimi (2016) applied pulse-decay on fractured Eagle Ford and Haynesville shales with the maximum effective stress of 2000 psi and pore pressure of about 700 psi. He collected three to four data points per series to investigate pressure and stress-dependent porosity and flow capacity for both the matrix and fracture, by the approach of history matching the upstream and downstream pressure curves. After reviewing his collected data points, it can be found that trends of these target properties as functions of pore pressure/stress are not very consistent. In the authors' opinion, three to four data points might be not enough to represent the whole pressure range especially when the range covers several hundred psi that the conclusions from the trend analysis might be questionable. We believe that a large set of experimental data pool are required to evaluate the feasibility of simultaneously estimating petrophysical properties of the matrix and fracture using the pulse-decay technique, which is the first objective of this study. The second objective is to use discrete fracture model (DFM) to characterize the transient flow process at the core-scale. DFM, representing fractures explicitly, has come to play an important part in fractured reservoir simulation. It has the advantage of better capturing the transfer phenomenon between the matrix and fractures and expressing fractures with various shapes (Huo and Gong, 2010; Liang et al., 2016). However, to the best of our knowledge, until now, no work has been presented in the open literature using DFM to simulate the transient pressure transmission process at the core-scale to interpret the effective permeability. Therefore, we aimed to fill this gap by comprehensively studying effects of multiscale features including heterogeneity, fracture, and vugs.

Our objectives of this study are to (1) construct a two-dimensional model to evaluate effective permeability ratio of complex tight porous media in the presence of fractures and vugs, based on the analytical solution describing the transient flow process, and compare the transient method with the steady-state method; (2) establish a large data pool by conducting pulse-decay experiments on fractured cores under different pore pressure and effective stress and estimate the matrix and fracture permeability, porosity and permeability dependency on the pore pressure and the effective stress by history matching the upstream and downstream pressure curves.

2. Numerical study based on DFM

In this section, we presented the construction of a 2D DFM to determine the ratio of effective permeability of complex core configurations over that of the matrix numerically. We included heterogeneous, fractured, vuggy, fractured and vuggy scenarios to evaluate the extent of permeability change due to the presence of heterogeneity, fracture, and vugs in the test core sample. Both the transient method and the steady-state method were applied to evaluate the effective permeability ratio.

Fig. 1a shows three main components of the pulse-decay system: upstream reservoir (U), core and downstream reservoir (D). Fig. A1 shows the schematic for the experimental set-up. The first, second, and third rectangular part represent the upstream reservoir, core, and downstream reservoir, respectively. The upstream reservoir is connected to the core, and its initial pressure is higher than the core pressure. The model is built in COMSOL Multiphysics 5.2a. No-flow boundary conditions are exerted on the outlines of the schematic.