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A fully coupled multiscale shale deformation-gas transport model for the evaluation of shale gas extraction

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ABSTRACT

Horizontal drilling and hydraulic fracturing are two enabling technologies to create a shale gas reservoir. For the created reservoir scale, we define shale blocks between hydraulic fractures as matrixes. In the matrix scale, flow processes are defined in the components of inorganic minerals and kerogens, respectively. Under this framework, a set of partial differential equations are derived to define various flow and deformation processes: (1) mechanical equilibrium equation that defines the shale deformation; (2) gas flow in the kerogen system of matrix; (3) gas flow in the inorganic system of matrix; and (4) gas flow in the hydraulic fracture system. For each of gas flow systems, a permeability or diffusivity model is derived to define its evolution. All systems are fully coupled through these permeability models and mass exchanges between different systems. The fully couple PDE system was solved by using COMSOL, a popular PDE solver. The model was verified against gas production data from the Marcellus Shale and the Barnett Shale, respectively. The verified model was applied to investigate the impact of adsorption parameters, flow regimes (Knudsen number), initial permeability of the inorganic matrix, and the effective stress variations on the gas production. Model results show that the Langmuir parameters affect both the cumulative gas production and the gas extraction processes; that the impact of flow regimes is closely related to the initial permeability of the inorganic matrix; and that the impact of effective stress variations on the permeability of hydraulic fractures is more significant than that on the matrix system.

1. Introduction

For most shale reservoirs, hydraulic fracturing and horizontal drilling are the key techniques to extract natural gas. Naturally, there are many nanopores, micropores and microcracks within shale rocks. Hydraulic fracturing can create many bigger fractures within the reservoir, which provide main flow paths into the horizontal well. This approach can reduce the length of flow path in the matrix and increase the contact area to the high permeability zones. We divide the whole reservoir into two sections. One is the hydraulic and induced fractures, which are the critical paths for gas transport into production wells. The other is the matrix between hydraulic fractures. When gas is produced from the reservoir, the free gas in the hydraulic fractures will flow out firstly. Then the gas in the matrix will transfer into these fractures, which supply the natural gas production. Therefore, the matrix plays a critical role in the gas depletion over the whole life time of the reservoir.

In order to accurately evaluate the gas production rate of a shale reservoir, it is important to consider different flow mechanisms within different scales and dynamic reservoir properties. Many scholars adopt the continuum mechanics model to investigate the gas flow within shale reservoirs. Specifically, both the single porosity single permeability model [1] and dual porosity dual permeability model [2–5] are used to represent the gas flow within the shale matrix. For the single porosity model, it is assumed that the porous medium is made up of uniform pores with the same properties, which ignores the differences between big cracks and small pores. Gas flow in the matrix is controlled by Darcy's law and mass conservation law. This method is useful for some porous medium without wide pores scale such as sandstones and soil. However, for the gas shale reservoir, many researchers noticed the big differences between inorganic matrixes and kerogens within the shale blocks [6–8]. Dual porosity model seems more reasonable because it takes into account the differences between the two systems. For example, the kerogen has the capacity of adsorption and the most adsorbed gas is stored in kerogen. Adsorption induces swelling of the matrix.

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Another difference is that the pores radiuses in kerogen are nanometers while those of inorganic matrix are microns. For both the micropores and nanopores, slippage effect is an important factor for gas transport mechanisms. In recent years, it is accepted that the mass transfer mechanism for gas in cracks or macropores is viscous flow while the transport mechanism for gas in kerogen is Knudsen diffusion and slip flow [6,8,9].

Dual porosity models provide well understanding for gas transport mechanisms within the kerogen and inorganic matrix. The coexisting mechanisms for mass transport like desorption, Knudsen diffusion, surface diffusion and Darcy flow are adopted in the simulations. However, most models ignored the dynamic behaviors of matrix properties like permeability and porosity. When the gas is depleted from the reservoir, the gas pressure in both inorganic matrix and kerogen will decrease to a lower magnitude. Effective stress within the matrix will be changed. This variation of effective stress will affect the average pores radius of the matrix, which means that the intrinsic permeability is a variable. In previous studies, many scholars did not consider the variation of stress and just focused on the gas flow principles. However, for the real reservoir simulation, the shale matrix deformation will play an important role in the gas production. Also, the matrix deformation can affect the mechanical properties such as porosity and permeability. In this study, we studied the coupled relationship among solid deformation, gas flow in matrix, gas diffusion in kerogen and gas flow in the hydraulic fractures.

In terms of the dynamic behaviors of porosity and permeability for the shale matrix, some researchers accepted the fact that the permeability is not a constant when the effective stress changes [10–13] and many experiments supported this conclusion. However, they did not consider the impact of flow regimes on the permeability of shale matrix. Actually, the apparent permeability is a function of flow regimes (Knudsen number), which means that flow regimes are also an important factor for the evolution of permeability in shale matrixes [14–19]. In the previous study, we established a dynamic apparent permeability model, which contains the effects of both effective stress and flow regimes. In this study we use this model to represent the dynamic permeability for inorganic matrix including the effects of adsorption, flow regimes and effective stress. It is appropriate to take the dynamic permeability and porosity into account when we adopt the dual porosity model to simulate the shale reservoir. The apparent permeability for kerogen system is developed as well. For the hydraulic fractures, a fracture flow model is applicable to describe the gas transport into the horizontal well. Experimental results indicate the effective permeability of the propped fractures decreases with the decrease of gas pressure [20,21].

Generally, we established three coupled fields for gas flow within matrix blocks. Based on the conventional dual porosity dual permeability model, we added solid deformation field into the coupled model. Specifically, one field is solid deformation which reflects the change of effective stress. Another field is gas flow within inorganic matrix or natural fractures with dynamic apparent permeability. The last field is gas flow within the kerogen system, which includes the effect of desorption, surface diffusion and effective stress. Combined with the fracture flow within the hydraulic fractures, the fully coupled gas transport mechanisms for gas shale reservoirs have been developed to analyze the gas production behaviors in the whole depletion period. Then, we analyze the impacts of flow regimes, effective stress and adsorption on the production rate.

2. Conceptual model

Hydraulic fracturing is a critical technique to stimulate the production of shale reservoirs. After fracking, the whole reservoir can be divided into two sections. One section is hydraulic fractures and another section is matrixes with many nanopores as shown in Fig. 1. Previous studies showed that fracture properties play an important role in reservoir performance in the early life of a shale gas well. However, it is the matrix properties that control the gas flow behaviors over longer periods of time [7].

In our previous study [22], we adopted continuum approach to investigate the gas flow and deformation laws of shale matrix based on single porosity model. This method is applicable for porous medium with uniform pores. That study demonstrated the importance of flow regimes and effective stress on the apparent permeability of tight porous medium. But it is noticeable that shale matrix is not a uniform material. Recent studies have shown that pores contain interparticle pores, intraparticle pores with inorganic matrix and nanopores in kerogen [23]. There are many differences between kerogens and inorganic matrixes. On the one hand, different pores scales mean different flow regimes such as slip flow, transition flow or diffusion, which have significant impacts on the gas transport mechanisms. Fig. 2 shows that the pores or cracks in inorganic matrix varies from hundreds nanometers to microns but pores in kerogen varies from several nanometers to hundreds nanometers. On the other hand, the adsorption capacities for kerogen and inorganic matrix are different. For kerogen system, adsorbed gas in organic grains may account for the biggest percentage of total storage gas, while for inorganic materials the volume of free gas is the biggest portion. Also, adsorption will induce matrix swelling, which can change the average pores radius of porous medium. In this study, a dual porosity dual permeability model for shale matrix is established to analyze the flow performances of kerogen and inorganic matrix separately. This conceptual model considers the interactions between kerogens and inorganic matrixes.

The dual porosity model for shale matrix can accurately represent the dynamic process of gas flow including desorption-induced shrinkage and Knudsen diffusion in nanopores of kerogen. Both flow regimes and effective stress have important effects on the apparent permeability of inorganic matrix and the diffusivity of kerogen. Generally, viscous flow will play the dominant role in gas transfer within inorganic matrix because Knudsen number is less than 1 while Knudsen diffusion contributes to the gas transport in kerogen. This model includes different fields within shale reservoir namely solid stress filed, gas flow in kerogen system, gas flow in inorganic matrix system and fracture flow in hydraulic fractures as shown in Figs. 3 and 4. Specifically, for the kerogen system, it has a strong affinity for the natural gas and nanopores have

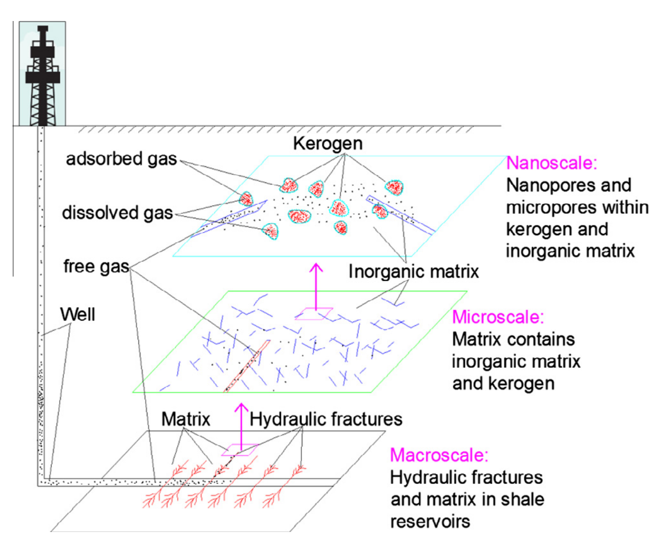

Fig. 1. The difference of fractures and matrix system in shale reservoirs.