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# Effects of non-Darcy flow on the performance of coal seam gas wells

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ABSTRACT

Although it has been reported that the gas flow in the cleat system may be of the non-Darcy nature, little has been known on how this non-Darcy flow affects the coal seam gas (CSG) extraction. One of the major reasons is that prior studies on this subject have not included the impact of gas sorption-induced coal deformation (swelling or shrinking) and the nature of two extremely different time scales between processes in the coal matrix and ones in the cleat system. In this study, a fully coupled finite element (FE) model of coal deformation (gas sorption induced swelling or shrinking), non-Darcy flow in fractures and gas diffusion in coal matrix is developed to quantify these non-Darcy flow effects. The fully coupled model can include EDM (Equilibrium Desorption Model) or DDM (Dynamic Desorption Model). In EDM, the gas sorption in the matrix system is a function of gas pressure only, i.e., the sorption process completes instantly when the cleat pressure changes. In DDM, the gas sorption in the matrix system is a function of both gas pressure in the cleat and the diffusion time in the matrix, i.e., a time lag between the cleat flow and diffusion process in the matrix exists. When only Darcy flow is assumed, this model was verified against both the model results of a vertical gas well performance by using ECLIPSE and field data from the Horseshoe Canyon coalbed gas well. Both EDM and DDM are applied to quantify the relationship among non-Darcy effect, production parameters, diffusion times, and coal seam compaction. Model results indicate that the non-Darcy effect is significant for high pressure drops and exists only within a small region near wellbore and that different diffusion times may produce two peaks of production rate, one is due to gas flow in the cleat system at the early stage and the other is due to gas diffusion at the late stage. The coal seam compaction can reduce the production rate much more than the non-Darcy flow effect at the early stage but has slightly impact at the late stage.



## 1. Introduction

Significant effects of non-Darcy flow on both conventional gas production and unconventional gas (such as coal seam gas) extraction have been observed (Clarkson et al., 2007; Zeng and Zhao, 2007; Zeng et al., 2003). The gas flow in porous media is pressure-driven and usually described by Darcy's law. The Darcy's law describes a linear relationship between Darcy velocity and pressure gradient. Any flow deviated from this linear relationship is defined as non-Darcy flow. From a series of coreflooding tests on Dakota sandstone in laboratory experiments, Zeng et al. (2003) found that with the increase of overburden and in-situ stress, the permeability of cores decreases while non-Darcy flow coefficient increases. Zeng and Zhao (2007) found that the parameter $b$ in the Arps' decline equation could be used to identify the non-Darcy flow from production data. They applied their method to a gas production well in a prolific gas-bearing to shaly sandstone reservoir located in the San Juan Basin and found that severe reservoir non-Darcy flow may cause the Fetkovich method to overestimate the drainage area of this well (Engler, 2000). Zeng and Zhao (2010) further investigated the effect of non-Darcy flow globally distributed in the gas reservoir on the pressure responses and locally distributed in the hydraulically fractured zones. They analyzed a gas well production with the Forchheimer non-Darcy flow at different bottom-hole pressures and found that under the condition of constant pressure drawdown the more severe the non-Darcy flow, the larger the Forchheimer number. The non-Darcy flow results in a smaller production rate, a larger decline rate in the boundary-dominated period, and a longer transition period between these two periods. Clarkson et al. (2007) conducted the production-data analysis for a single-phase coal seam gas (CSG) well and found that the gas production rates were different at the early time and the later time. Tavares et al. (2006) addressed the combined effect of non-Darcy flow and formation damage on gas well performance using simplified analytical solutions and a 2D numerical simulator for naturally fractured reservoirs. They found that skin damage may accentuate the non-Darcy flow effect, leading the conventional interpretation of the early-time data to erroneous results. After analyzing the production data using the Fetkovich method, they observed that for the fractures dominated well performance, the lower the formation

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permeability, the greater the non-Darcy pressure gradient. Non-Darcy effect may cause the estimated damage to be as such as 5 to 15 times higher than the actual physical damage, particularly at the early time. They pointed out that non-Darcy flow could significantly influence the calculation of physical skin damage and effective permeability even in a homogeneous reservoir. Guo et al. (2004) numerically investigated the effects of non-Darcy flow and coal skeleton deformation through their explicit algorithm which coupled the coal seam gas flow and the change of porosity and permeability of coal seam. They found that the change of porosity and permeability of coal seam can reduce the production rate much more than non-Darcy flow effect but they did not consider the non-Darcy effect at different production stages. As a summary, the above-mentioned analyses found that non-Darcy flow is an important factor to the reduction of production rate, particularly in fractured reservoir such as coal seam reservoirs at the early time.

The unique nature of CSG reservoirs may accentuate the significant non-Darcy effect on the CSG extraction. As an unconventional gas, the coal gas storage and transport mechanisms differ substantially from the conventional reservoirs (Clarkson and Bustin, 2011; Engler, 2000; Liu et al., 2011) because coal seam gas reservoir is highly heterogeneous. This heterogeneity is usually characterized by two distinct pore systems — micropores in coal matrix and macropores in fracture network. The micropores exist in the coal matrix and provide extremely large internal surface area with a strong affinity to methane. It has been found that the micropores in coal matrix serve as storage spaces for over 95% of the total gas available in absorbed form (Gray, 1987; Harpalani and Chen, 1997; Pillalamarry et al., 2011). The coal matrix has very low permeability (Bustin and Clarkson, 1998). The macropore system consists of a natural network of closely spaced fractures called as the cleat system. It provides the primary pathways for gas flow in coal (Izadi et al., 2011; Ma et al., 2011; Pillalamarry et al., 2011). The cleat spacing is fairly uniform, ranging from a fraction of an inch to several inches (Rogers, 1994). From their geometry, macro-fracture network isolates the matrix into individual blocks (Liu and Rutqvist, 2010) and the permeability of the coal is dominated by the macro-fractures (Lu and Connell, 2011; Van Golf-Racht, 1982). How this heterogeneous system is modeled for the CSG production process is an interesting but challenging topic (Perrin and Benson, 2010; Uh and Watson, 2010).

Single porosity models were proposed to address the coal deformation effect on the evolution of porosity and permeability. For example, Seidle and Huitt (1995) regarded that only sorption-induced strain can change the permeability. Their Seidle–Huitt model did not include the elastic strain of coal seam. In the famous Palmer–Mansoori model (Palmer and Mansoori, 1998), only uniaxial stress condition of the elastic deformation of coal was considered. Under this condition, the effective volumetric strain is equal to the vertical effective strain. Thus the evolution of porosity is expressed in terms of the compression due to pore pressure and the swelling of coal due to the change of sorption capacity. Further, the evolution of permeability is related to the evolution of porosity through a cubic law. Some researchers directly used exponential forms to formulate either porosity or permeability model or both (such as Cui and Bustin (2005), Robertson and Christiansen (2006), Shi and Durucan (2004), as well as Guo et al., 2004; Gu and Chalaturnyk, 2010). Their differences lie in the calculation of formation compressibility. Zhang et al. (2008) proposed a general porosity model based on the volumetric deformation analysis of porous medium. They also used the cubic law to link porosity model with permeability model. In their model, the evolution of porosity depends only on the change of effective volumetric strain which usually has three components: volumetric strain of coal skeleton due to effective stress, the compressibility of coal particles due to pore pressure and other volumetric strain due to non-mechanical actions such as swelling and heating expansion. In order to consider the heterogeneity of coal seam, Liu et al. (2011) extended this concept of effective volumetric strain to dual-porosity system by introducing a local effective volumetric strain. This concept can make the porosity and permeability independently evolve in the matrix and fracture systems. However, they did not consider the non-Darcy flow except the work by Guo et al. (2004).

Dual porosity models were widely used to characterize the heterogeneity of coal seams (Wu et al., 2010a). In these models, fractures are highly permeable and matrix blocks are of low permeability. The gas competitively flows in both fracture network and interstitial matrix. These models can describe the response of these two principal components only — gas release from storage in the porous matrix and gas transport in the fracture network (Warren and Root, 1963; Wu et al., 2010a, 2010b). Choi et al. (1997) proposed a dual-porosity and dual permeability model with non-Darcy flow through fractures. They supposed that the flows in both matrix block and fractures still follow the Darcy law but the source term of fractures flow has to consider the non-Darcy flow effect through the Forchheimer law. Guo et al. (2004) addressed the coupling of non-Darcy flow and coal skeleton deformation in coalbed methane reservoirs. They proposed an explicit algorithm in which flow calculations are performed every time step and the changes of porosity and permeability of coal seams are calculated only at selected time steps. They studied the effects of non-Darcy flow and coal deformation on production rate and found that the decrease of porosity and permeability in the coal seam reduces the gas production rate much more than non-Darcy flow effect. Their model did not take the sorption-induced swelling into account. Unsal et al. (2010) proposed a numerical model for multiphase flow in fractured reservoirs using a fracture-only model with transfer functions. In their model, fracture geometry is modeled explicitly, while fluid movement between fracture and matrix is accommodated using empirical transfer functions. This approach retains the main flow paths of complex fracture geometry and the transfer functions simplify meshing and make the simulation method considerably more efficient than discrete fracture discrete matrix models. Their model can capture both the early-time and late-time average pressure. Further development include the mechanical effect such as the analytical models for dual porosity media with averaged elastic components (Aifantis, 1977), mechanical constitutive laws within dual (Elsworth and Bai, 1992) and multi-porous media (Bai et al., 1993). Such models have been applied to investigate the response of permeability evolution in deforming aquifers and reservoirs (Liu et al., 1999). As a summary, the models as mentioned above were primarily developed for the flow of slightly compressible liquids and later extended to the flow of compressible fluids with gas adsorption, but they assumed that Darcy law is applicable to cleat system, matrix and their exchange flow. No formation compaction and no time scales in the cleat system and matrix are considered.

Darcy-diffusion dual-porosity model addressed the two-time-scale mechanisms of gas flow in the fractured coal seam (King et al., 1986). Two different mechanisms were observed for the gas transport in coal seam: pressure-driven flow (Darcy flow) in the cleat system and concentration gradient-driven flow (diffusion flow) in the coal matrix. The diffusion flow has different mechanisms. As pointed out by Pillalamarry et al. (2011), the single process of micropore diffusion is usually a combination of three types of diffusion: Knudsen (where molecule–wall collisions dominate), surface (transport through physically adsorbed layer) and bulk (molecule–molecule collisions dominate) (Shi and Durucan, 2003). When the mean free path of the gas molecules is greater than the molecular diameter, or when the pressure is very low, Knudsen diffusion takes place, and gas molecules flow from higher to lower gas concentration (Collins, 1991). In this mechanism, the gas molecules collide more frequently with the walls of the flow paths than with other molecules. Broadly, the resistance to flow is not due to the intermolecular collisions, but rather due to gas molecules colliding with pore walls. Bulk diffusion, on the other hand, is the opposite of Knudsen diffusion, occurring at higher pressures (Collins, 1991), or where the pore diameter is larger than the mean free path of gas molecules. The resistance to diffusion