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Evaluation of the non-Darcy effect in coalbed methane production

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HIGHLIGHTS

- A coupled model is developed to study non-Darcy flow in coal.
- Variable β factor as function of permeability is coupled.
- Constant β factors may significantly under or over estimate production rate.
- Evolution of non-Darcy factor becomes tortuous with variable β factor applied.
- Increasing coal cleat compressibility intensifies the tortuous behavior.

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ABSTRACT

The non-Darcy factor, an indicator for the non-Darcy effect, is dependent on the properties of porous media and pore fluid including permeability, viscosity, density, flow velocity and a coefficient named as β factor. Experimental results show that the β factor can be expressed as a power law of permeability. For conventional gas reservoirs, this β factor can be assumed as a constant as the permeability change is negligible. However, the constant β factor may not be suitable for coal seams with remarkable permeability change and a variable β factor as a function of coal permeability should be an alternative. Moreover, the coal permeability change is complex due to the competing effects of coal cleat compression and sorption induced coal shrinkage/swelling. Few studies have been done previously to incorporate the variable β factor as a function of coal permeability in reservoir simulations. In the present work, both the coal permeability change and the variable β factor are coupled in a dual porosity model to study the non-Darcy flow behavior in coal seams. The simulation results illustrate that the evolution of non-Darcy factor becomes tortuous by using a variable β factor, which differs from the monotonic behavior when constant β factors are applied. Furthermore, increasing the coal cleat compressibility and matrix shrinkage strain tends to intensify the tortuous behavior. The simulation results also indicate that using typical constant β factors, instead of the variable one, may significantly underestimate or overestimate the gas production rate for coalbed methane wells.

1. Introduction

Coal seams are the dual porosity media with micropores in coal matrix and macropores in coal cleats. Most gas in coal seams is originally adsorbed on the surface area of coal matrix rather than stored as a free gas [1]. The coal matrix plays a role as the gas source while the coal cleat network provides main paths for gas flow. Different mechanisms govern the gas transport in this dual porosity coal seam [2–5]: the gas transport in coal matrix is the diffusion process governed by Fick's law and the viscous flow in coal cleats is normally described by Darcy's law. The Darcy's law expresses a linear relation between pressure gradient and flow velocity. When the flow velocity is higher than a certain level, this pressure gradient does not follow this linear relation with flow velocity. This non-linear relation is defined as the non-Darcy flow. The non-Darcy flow behavior has been observed in some fields and laboratories [6–8]. Their observations illustrated that the non-Darcy flow played an important role in fluid flow within both conventional and unconventional hydrocarbon reservoirs. The Forchheimer equation [9] has been proposed to describe this non-Darcy flow in porous media [10] where a term signifying the non-Darcy effect was added to the Darcy's law. Thereafter, Holditch and Morse [7] introduced a non-Darcy factor f_T to express the permeability ratio of non-Darcy flow to the Darcy's flow, which is the indicator of non-Darcy effect. The value of non-Darcy factor f_T

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ranges from 0 to 1.0. Once the non-Darcy factor f_T goes smaller than 1.0, the non-Darcy flow takes effect. Smaller f_T represents stronger non-Darcy effect.

The non-Darcy flow has been considered in modeling the flow behaviors in conventional reservoirs. Ramey [11] found that the non-Darcy flow could distort the early pressure distribution around gas well and suggested to consider this effect in estimating the variations in flow capacity in short-time gas well testing. Tariq [12] proposed a 3D finite element model of steady-state flow in perforated completions with and without the non-Darcy effect for a linear core. His work has been developed to a commercial package SPAN (1999) based on semi-analytical expression proposed by Karakas and Tariq [13]. Wang et al. [14] studied the anisotropic non-Darcy flow behavior at the pore-scale and found the non-Darcy term was proportional to the square of the superficial velocity at the macroscopic scale. Miskimins et al. [15] investigated the non-Darcy flow in several cases of hydraulic fractures and found that the non-Darcy effect was able to reduce the cumulative gas production by up to 18.1% over a ten-year period. Jamiolahmady et al. [16] studied the behavior of single-phase steady-state flow in a perforated core by conducting steady-state core experiments and numerical modeling via Femlab mathematical package (now updated as COMSOL Multiphysics) and considering the non-Darcy flow in crushed zone and the effect of inertia.

Few experimental and field studies were conducted on the non-Darcy flow in coal seams, although the non-Darcy effect in sandstone, limestone [6,7] and tight gas reservoir [8] was extensively studied. Several simulations have been carried out to investigate the non-Darcy effect on the gas flow through coal seams [17–20]. These simulations illustrated that the gas flow behavior around the wells could be significantly affected by the non-Darcy behavior. More fundamental works are necessary to investigate the characteristics (e.g. the existence, the influencing region and the magnitude) of non-Darcy flow in coal seams. The coal permeability change plays an important role in estimating gas flow ability in coal seams. It has been observed in both laboratories and fields that the coal permeability change could reach up to four magnitudes [21]. It is believed that the coal permeability change is mainly controlled by two main factors: coal cleat compression and sorption induced shrinkage/swelling [22,23]. The non-Darcy factor, an indicator for the non-Darcy effect, is dependent on many parameters including permeability, viscosity, density, flow velocity and a coefficient named as β factor. For conventional gas reservoirs, this β factor can be assumed to be unchanged as the permeability change is negligible. However, the constant β factor may not be suitable for coal seams with a huge permeability change and a variable β factor as a function of coal permeability should be applied.

This paper investigates the non-Darcy effect in coal seams through reservoir simulations. The characteristics of non-Darcy flow in coal seams have been investigated through a quantitative study on the non-Darcy factor f_T. A series of simulation scenarios were conducted to illustrate the distribution and evolution of non-Darcy factor f_T with different coal properties, e.g. initial coal permeability, coal compressibility, initial reservoir pressure, etc. The effect of non-Darcy flow on the pressure distribution and the gas production rate were investigated by coupling the non-Darcy factor f_T in the simulation model.

2. Non-Darcy factor and numerical model

The basic principles and the key parameters for the non-Darcy flow are briefly described here. The definition of non-Darcy flow in porous media is presented prior to the introduction of non-Darcy factor. Then a numerical simulation model is introduced to investigate the non-Darcy behavior in coal seams.

2.1. Non-Darcy flow and non-darcy factor

The Darcy's law is expressed as:

$$\frac{\Delta p}{\Delta L} = \frac{\mu}{k} u \tag{1}$$

where μ is the fluid viscosity and k is the coal cleat permeability. Δp is the pressure drop over flow path of ΔL.

In the Darcy's law, the pressure gradient $\Delta p/\Delta L$ is proportional to the flow velocity u. When the velocity increases, the flow can change from laminar to turbulent flow, and the pressure drop shows a non-linear relation with velocity due to inertial resistance and/or turbulent flow [24–26]. This non-linear behavior can be described by adding a quadratic term of the velocity to the right hand side of Eq. (1) [9], which is often named as the Forchheimer equation. Cornell and Katz [10] replaced the coefficient in Forchheimer equation by the product of the fluid density ρ and the β factor, a characteristic parameter of the porous media:

$$\frac{\Delta p}{\Delta L} = \frac{\mu}{k} u + \beta \rho u^2 \tag{2}$$

Eq. (2) is a general relationship between pressure drop and flow velocity for turbulent flow. If the β factor or flow velocity u approaches zero, then the second term in Eq. (2) can be ignored and Eq. (2) degrades to Eq. (1).

Several studies have been conducted to correlate the β factor with permeability of the porous media [6,8,24,27]. Cooke [6] investigated non-Darcy flow for fractures packed with multiple layers of sand and suggested that β factor could be expressed as a power law of permeability k:

$$\beta = a \cdot k^b \tag{3}$$

where a and b are the reservoir- specific coefficients.

This empirical equation makes it easier to estimate the non-Darcy behavior by knowing the permeability of the reservoirs. In addition, Friedel and Voigt [8] have found that this power law was also valid for tight-gas reservoirs.

To incorporate the non-Darcy effect into reservoir simulation, Holditch and Morse [7] introduced a non-Darcy factor f_T, which is defined as the ratio of equivalent permeability of non-Darcy flow k_T to that of Darcy flow k:

$$f_T = \frac{k_T}{k} = \frac{1}{1 + \frac{k}{\mu} \rho \beta u} \tag{4}$$

The non-Darcy factor f_T can be derived by comparing the Darcy's law and the Forchheimer equation [7]:

$$\frac{\Delta p}{\Delta L} = \frac{\mu}{k} u + \beta \rho u^2 = \left(\frac{\mu}{k} u\right)\left(1 + \frac{k}{\mu} \rho \beta u\right) = \frac{\mu}{k f_T} u = \frac{\mu}{k_T} u \tag{5}$$

where k is the permeability measured under Darcy flow condition and k_T is the equivalent permeability under non-Darcy flow condition.

This non-Darcy factor, a correction parameter of permeability for Darcy flow, is a measure of degree of non-Darcy flow through porous media. As an indicator of non-Darcy flow, the value of non-Darcy factor f_T ranges from 0 to 1.0. Once the non-Darcy factor f_T goes smaller than 1.0, the non-Darcy flow takes effect. Smaller f_T represents stronger non-Darcy effect.

2.2. Numerical model

The non-Darcy flow characteristics can be revealed by studying the distribution and evolution of the non-Darcy factor (f_T). To calculate the non-Darcy factor with Eq. (4), the following parameters should be obtained: (1) the fluid (methane) property parameters