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Benchmark assessment of coal permeability models on the accuracy of permeability prediction

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HIGHLIGHTS

- Performances of coal permeability models were benchmarked against correct solutions.
- Assumptions of uniaxial stress, constant overburden stress and local equilibrium were removed.
- The effective stress transfer between matrix and fracture were included.
- These three assumptions were identified as the reason of coal permeability model failures.

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ABSTRACT

When natural gas is extracted from coal seams, complex interactions of stress and sorptive chemistry have a strong influence on the properties of coal. These include influences on gas sorption and flow, coal deformation, porosity change and permeability modification. In this study, we define this chain of reactions as "coupled processes" implying that one physical process affects the initiation and progress of another. The individual process, in the absence of full consideration of cross couplings, forms the basis of the conventional coal seam gas reservoir engineering. Therefore, the inclusion of cross couplings is the key to rigorously formulate the unconventional coal seam gas reservoir engineering. Among those cross-couplings, the coal permeability model is the most important one. A variety of permeability models were developed to define how the coal permeability evolves during gas production. These models were derived normally under three common assumptions: (1) uniaxial strain; (2) constant overburden stress; and (3) local equilibrium. Under these assumptions, coal permeability can be defined as a function of gas pressure only. Our comprehensive review concluded that these models have so far failed to explain experimental results from conditions of the controlled stresses, and only partially succeeded in explaining in situ data. We identified the adoption of these three assumptions as the fundamental reason for failures. In this study, we relaxed the first two assumptions and derived a coal permeability model under variable stress conditions. Furthermore, we considered the effective stress transfer between matrix and fracture and transformed this stress transfer into the modification of fracture aperture. This relaxes the third common assumption, i.e., local equilibrium condition. We applied this approach to generate a series of permeability type curves under the full spectrum of boundary conditions spanning prescribed stresses through constrained displacement. We benchmarked the solutions generated by using the permeability models with three common assumptions against our "accurate" solutions by using permeability models without these assumptions for the full spectrum of boundary conditions, and concluded that these common assumptions could produce unacceptable errors.

1. Introduction

From in situ and experimental observations, permeability of a coal seam gas reservoir is not constant during depletion of the coal-bed methane (CBM) since gas extractions trigger complicated

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gas–coal interactions. Acid gases like methane originally adsorb around surface of coal, causing a sorption-induced strain in reservoirs. When CBM is extracted from coal seams, gas desorbs from coal surface and coal matrix shrinks. This coal matrix shrinkage may increase coal permeability while the rising effective stress due to the drop of pore pressure can lead to the decline of permeability [1,2]. Furthermore, other factors, like heterogeneity of coal, gas composition and water content, also contribute to the complexity of gas–coal interactions [3–5]. All of these lead to permeability hardly be predicted and change dramatically: up to 100 times in the San Juan basin [6]. Moreover, permeability of a reservoir has a close relationship with productivity of CBM. Information on permeability is in favor of long-term production design. However to obtain information on permeability in the field is very expensive since it requires multi-well tests [7]. Therefore, a mathematical model of determining changes in permeability is very valuable.

A number of permeability models for coal have been proposed under specific assumptions. Table 1 lists current permeability models and their assumptions. Uniaxial strain and constant overburden stress are regarded as usual boundary conditions in reservoirs. Most of early permeability models were proposed based on these two assumptions. Gray [8] first incorporated the effect of matrix shrinkage into permeability model and considered effective horizontal stresses controlled changes of permeability. Gilman and Beckie [9] presented a simplified geometry model for CBM and corresponding mathematical model of permeability which also contains the release mechanism of methane from matrix into cleats. Shi and Durucan [10] improved the model proposed by Gray and considered the volumetric matrix shrinkage is proportional to the volume of desorbed gas rather than to reduction in the equivalent sorption pressure. Palmer and Mansoori [11] (called as P&M model later) derived a widely used theoretical permeability model which is a function of effective stress and matrix shrinkage. The P&M model was improved and summarized by Palmer et al. [12]. The geometry of all these models except Gilman and Beckie model that had a simplified geometry was matchsticks model.

Usually, the uniaxial strain condition is invalid in laboratory. To obtain permeability suitable for laboratory conditions, cubic geometry model instead of matchsticks geometry was applied. Schwerer and Pavone [13] developed a permeability model for laboratory measurements under the constant overburden stress condition. Pekot and Keeves [14] improved that model, considering the effect of matrix shrinkage on the permeability. They assumed that matrix shrinkage was proportional to the adsorbed gas concentration change multiplied by shrinkage compressibility. Roberson and Christiansen [15] further relaxed the constant overburden stress assumption and presented a new equation that can be used to model the permeability behavior of a fractured, sorptive-elastic media under variable stress conditions commonly used during measurement of permeability data in the laboratory. From constitutive relation for poroelastic media, Cui and Bustin [16] developed a general stress-based porosity and permeability model for deep coal seams, considering effects of reservoir pressure and sorption-induced volumetric strain on permeability.

Currently, it was pointed out that constant overburden stress condition is invalid near the wellbore. The stress arching exists above a wellbore due to the cylindrical hole not supporting any overburden directly above it [17]. Therefore, permeability models under usual assumptions may be inaccurate for reservoirs. In recent years, significant efforts have been made to develop permeability models without those usual assumptions. Gu and Chalaturnyk [18] proposed a permeability model. It overcame the usual assumptions and could reflect anisotropy in permeability and deformation. Following the similar method with Cui and Bustin, Zhang et al. [19] developed a strain-based porosity and permeability model based on theory of poroelasticity. It was shown that current commonly used permeability models could be treated as specific examples. Connell et al. [20] proposed two new analytical permeability models representing for standard triaxial strain and stress conditions.

Siriwardane et al. [21] conducted experiments and showed that permeability of adsorbing gas in coal is a function of exposure time. According to this, Liu et al. [22] believed that permeability changes related to the process of gas–coal interactions and proposed a permeability switching model. They explained why permeability under the influence of gas adsorption can switch instantaneously from reduction to enhancement and revealed the transition of coal matrix swelling from local swelling to macro-swelling under the unconstrained swelling condition. In accordance with their theory, all the other above permeability models have the other assumption: local equilibrium, which means that those models ignored dynamic interactions between matrix deformation and fracture aperture alternation. Currently, the conceptual dual porosity model was proposed by Wu et al. [23,24] and it could involve the effect of interactions between two systems on fracture permeability. Nevertheless, the permeability model used in this method was also the common one with the above assumption of local equilibrium.

As reviewed above, a wide variety of coal permeability models have been proposed. However, these models have only partially succeeded in explaining in situ data. Even like P&M model which is used widely to match in situ data among permeability models, its improved formation could match two different sets of San Juan data only with three rigorous preconditions [6]. Compared with experimental data, these models have so far failed to explain experimental results from conditions of the controlled stresses and even could not match the trend of experimental data. To solve this issue, Robertson and Christiansen [25] added a strain factor into these models. Results from these improved models had consistent trends with experimental observations but the

Table 1
Summary of current permeability models and their assumptions.

Proposed by	Assumption		
	Uniaxial strain	Constant overburden stress	Local equilibrium
Gray [8]	√	√	√
Gilman and Beckie [9]	√	√	√
Shi and Durucan [10]	√	√	√
Palmer et al. [11,12]	√	√	√
Schwerer and Pavone [13]		√	√
Pekot and Keeves [14]		√	√
Roberson and Christiansen [15]			√
Cui and Bustin [16]			√
Gu and Chalaturyk [18]			√
Zhang et al. [19]			√
Connell et al. [20]			√