A Review on Recent Advances in the Numerical Simulation for Coalbed Methane Recovery Process

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Abstract

The recent advances in numerical simulation for primary and enhanced coalbed methane (CBM/ECBM) recovery processes are reviewed, focusing primarily on the progress that have occurred since a similar review paper was published by King and Ertekin in 1989. Two major issues regarding the modeling will be focused on in this review: firstly, multicomponent gas transport in situ bulk coal and secondly, changes of coal properties during methane production. For the former issues, a detailed review of more recent advances in modeling gas and water transport within coal matrix is presented. Further, various factors influencing gas diffusion through coal matrix will be highlighted as well, such as pore structure, concentration and pressure, and water effects. An ongoing bottleneck for evaluating total mass transport rate is developing a reasonable representation of multi-scale pore space that considers coal type and rank. Moreover, few efforts have been involved to model water flow behavior in coal matrix and its effects on both CH4 production and on the exchange of CO2 and CH4. As for second issue, theoretical coupled fluid flow and geomechanical models have been proposed to describe the evolution of pore structure during methane production, instead of traditional empirical equations. However, there is currently no effective coupled model for engineering applications. Future perspectives of developing suitable simulation models for CBM production and predicting CO2-sequestration ECBM recovery are suggested.

Introduction

Coalbed methane has been recognized as a significant natural gas resource for a long time. Recently, carbon dioxide sequestration in coalbeds for enhanced coalbed methane recovery has been attracted growing attention due to greater concerns about greenhouse gas effect and emerging commercial significance of coalbed methane.

Reservoir simulation technology, as a useful tool of reservoir development, has the capability to provide us with an economic means to solve complex reservoir engineering problems with efficiency. Three types of CBM reservoir models are currently used to simulate CBM/ECBM processes based on the evolution of coalbed methane reservoir simulation techniques.

Conventional black oil and compositional model The gas diffusion in coal is generally assumed to occur instantaneously, and thus they are actually single-porosity models coupled with a gas source function. The source function is assumed as the gas dissolved in oil. This approach is not valuable for description of CBM recovery process due to a lack of supporting theory.

Specialized CBM model The non-equilibrium diffusion process (pseudo-steady state method) is modeled with a dual-porosity system. Additionally, various adsorption models are used to simulate the multicomponent gas adsorption equilibrium. This type of models is now widely used in modeling CBM/ECBM recovery. However, most of such models are still unable to give an acceptable accuracy because of the complicated physical and chemical conditions associated with CBM recovery processes of coal seams.

Improved CBM model More recently many attempts have been made to improve the CBM/ECBM simulation with alternative models, e.g. unsteady state model, bidisperse pore diffusion model, and triple-porosity simulation model. Additionally, several empirical equations were incorporated in simulator to describe the variation of coal properties due to coal matrix shrinkage. These studies are still at the early stage.

Although many people have briefly summarized the recent progress on coalbed methane reservoir simulation technology, a systematic understanding of coal gases and water transport kinetics during CBM/ECBM recovery warrants an up to date, comprehensive, and critical review on this topic.

Modeling gas sorption rate

Gas sorption rate is generally controlled by two processes: sorption process (sorption characteristic of the coal) and diffusion process (the diffusion of gas through the coal matrix). These two steps are usually lumped together in numerical models. So far the work found in the literature primarily focuses on the adsorption capacity and pays less attention to the gas diffusion in coal matrix, in particular the mixed gas counter diffusion.
Multicomponent gas sorption equilibria

Multicomponent gas adsorption equilibria in coal seams are described using following approaches:

The K-value method is initially modified to describe coal gas sorption equilibria. The modification involves using an immobilized oil phase to simulate the coal matrix, and the solution gas to simulate the adsorbing components. Thus this method is not an accurate model with firm theoretical basis.

Extended Langmuir isotherm was suggested to provide a reasonable fit to experimental binary and ternary gas adsorption data using single-component sorption isotherms (Arri et al., 1992; Harpalani and Pariti, 1993). However, it is not able to describe the thermodynamics of multi-component coalbed gas sorption accurately. Further, Clarkson (2003) found that if CO2 separation factor varies strongly with pressure for a particular coal composition or rank, the extended Langmuir model maybe not adequate for binary gas adsorption predictions due to a constant separation factor assumed in the extended Langmuir equation.

Thermodynamic approaches were found to be superior to extended Langmuir equation for total adsorption capacities and equilibrium component predictions. The approaches are typically the idea adsorbed solution (IAS) and real adsorbed solution (RAS) with real gas (RG) equation-of-state (EOS), especially the IAS theory. Stevenson et al. (1991) compared predictions of the IAS-RG and RAS-RG models with experimentally measured adsorption capacities of ternary gases (CH4, N2, CO2). The RAS-RG model fails to improve the sorption prediction using the IAS-RG model for high pressure due to inability to correctly predict realistic activity coefficients, while the IAS-RG model provides acceptable multi-component adsorption capacity predictions in many coalbed gas reservoir applications except high-pressure ternary gas system.

Clarkson and Bustin (1999) compared the predictions of IAS theory, based on Dubinin-Radushkevich (D-R), Dubinin-Astakhov (D-A) and Langmuir isotherm, respectively, and extended Langmuir isotherm with experimental binary gas isotherms (CH4, CO2). The results suggested that the IAS theory and extended Langmuir differ substantially in their ability to predict binary gas adsorption behavior, but IAS predictions are strongly dependent upon the choice of pure gas isotherm equation. For a system where CO2 selectivity varies greatly with gas pressure and composition, IAS/D-A model is more accurate than extended Langmuir isotherm, since the IAS/D-A theory predicts a decreasing selectivity with an increase CO2 concentration. This is consistent with experimental data and previous findings. The IAS/Langmuir model predicts the opposite: carbon dioxide selectivity increases with pressure and concentration.

The data of Hall et al. (1994) provided different results. The relative errors for total gas adsorption are comparable for the extended Langmuir and IAS models, but are variable for the single-component adsorption. The IAS/Langmuir and extended Langmuir equations provide, on average, a better fits to component data than the IAS/D-A and IAS/D-R models. The possible reason is the carbon dioxide selectivity varies slightly with pressure and CO2 concentration. For this case, the error introduced in the spreading pressure calculation make Langmuir equation fit the pure component isotherm better than the D-A and D-R equations.

Manik et al. (2002) validate IAS-PG and IAS-RG models (with Toth isotherm) using experimental data provided by Stevenson et al. (1991). The adsorption capacities predictions showed that both two models give better predictions for binary gas systems (CH4-N2 and CH4-CO2) at low system pressure than high pressure and the system of ternary gas mixture (CH4-N2-CO2). Furthermore, both IAS models give the same level of accuracy in the predictions of equilibrium concentration at low and relatively high pressures (600 psia) for binary gas mixtures. While for ternary gas mixtures at high pressure, derivations as high as 20% in mole fraction predictions were observed, indicating that increasing number of gas component in the mixture increases the non-ideality of the adsorbed gas behavior. Therefore, the overall results from IAS-RG model for binary system are better than for ternary system at high pressure.

Clarkson model (2003), developed through combining the vacancy solution and Dubinin-Polanyi theories, is a new multicomponent adsorption model for application to coal gas adsorption systems. This model allows, for the first time, to consider the produced gas composition evolution during primary depletion.

Simplified local density/Peng-Robinson model (SLD-PR) (2003) correlates the behavior of supercritical adsorption systems encountered in CBM recovery and CO2 sequestration. It is proved that this model improves pure-component adsorption capacity prediction for methane, nitrogen and CO2 adsorption on in-situ coal samples.

Most of current experimental and model studies are limited in the case that the system pressure is below the critical pressure of carbon dioxide. The IAS models are superior to extended Langmuir isotherm for total adsorption capacities and equilibrium component predictions, but it dependent on the pure component isotherm. Most of IAS models are accurate for binary and ternary gas adsorption at low system pressure, except for high-pressure ternary gas adsorption isotherm.

Modeling multicomponent gas diffusion kinetics

Three types of models are proposed to describe gas diffusion in coal matrix: no diffusion, one-step diffusion and two-step diffusion. Figure 1 illustrates the framework of current gas diffusion models used in CBM reservoir models.

A very good summary of the development of equilibrium and non-equilibrium model (pseudo-steady state and unsteady state formulations) for methane diffusion in coal matrix blocks has been presented by King and Ertekin in 1989. All of the reviewed models basically described gas diffusion process as instantaneous or one-step diffusion process respectively. More recently, researchers have realized that gas adsorption and diffusion in coal matrix with multi-scale pores can be described better by a bidisperse diffusion model.

The effective diffusivity is a key parameter in evaluating gas sorption rate in coal matrix. It is generally not constant during production, depending on the gas pressure, concentration, coal wettability and pore structure. Therefore, incorporating these effects in gas diffusion models is crucial to
describe CO₂-ECBM processes. From the perspective of numerical simulation, the following issues are of concern, i.e.:  
1) Pore-structure dependent diffusivity;  
2) Pressure and concentration dependent diffusivity;  
3) Multicomponent gas counter-diffusion process; and  
4) Water effects on exchange of CO₂ and CH₄.

Pore-structure dependent diffusivity
Coals demonstrate very different pore structure, sorption capacity and gas transport behavior due to coal rank, lithology and maceral effects. Correspondingly unipore diffusion model and bidisperse model are developed to model different types of gas diffusion processes respectively. So far most of existing diffusion models account for unipore gas diffusion process based on dual-porosity system. Only a few attempts have been made to model gas diffusion in coal matrix using bidisperse models.

Unipore diffusion model
The pseudo-steady state method based on the Warren and Root (1963) model of dual-porosity reservoirs is now used in most of commercial CBM simulators to describe coal gas sorption kinetics. Since the matrix response to changes in gas partial pressure is represented in a lumped parameter fashion, neglecting the true spatial variation of gas concentration, this approach is only accurate for large times, not for the early time.

The unsteady state approach is an alternative, which is more rigorous, but more expensive computationally to solve than the former, since it includes the effects of the gas concentration gradient. However, there are two problems with current unsteady state model, that is:  
1) It does not include the concentration-dependent diffusivity;  
2) whether the diffusion path length should be set equal to the equivalent particle radius.

Bidisperse pore diffusion model
The bidisperse models generally assume two-step gas diffusion in coal matrix: surface diffusion in microporous system and pore diffusion in meso- and/or macro-pore system. Gas adsorption takes place in the micropores, with the meso-/macro-pores providing storage for free gas, as well as tortuous paths for gas transport between the micropores and macropores. Table 1 compares the features of six bidisperse diffusion models developed to model gas diffusion in coals as well as other porous solids. The model illustrates the importance of pore connectivity in determining mass transport rate, without resorting to tortuosity factors. This is an important advantage since tortuosity factors cannot be determined by sound theoretical arguments, and in most cases can only be poorly estimated. However, the structural properties such as surface area and coordination number are empirically calculated using simulation results, which generally produce unreasonably high percolation thresholds. Specific expressions for the internal surface area of Bethe lattice pore structure are lacking.

Pressure and concentration dependent diffusivity
Current studies on this issue are very limited. Two factors are now recognized to induce the pressure-dependence of diffusivity: nonlinear isotherm and matrix swelling and shrinkage due to gas adsorption and desorption.

Nonlinear isotherm effects
In adsorption system when the equilibrium isotherm is linear, diffusion coefficient is generally independent of concentration. However, when the isotherm is nonlinear the diffusivity is concentration dependent. Since the driving force for diffusivity transport is the gradient of chemical potential, rather than the gradient of concentration, the Fickian diffusivity (D) is related to the intrinsic diffusivity (D₀) by

\[ \frac{D}{D₀} = \left( \frac{\partial \ln p}{\partial \ln q} \right)_T \]  

(1)

Where p is gas partial pressure, q is adsorbed phase concentration, and subscript T denotes temperature. Nandi and
Walker (1970) investigated the concentration dependence of effective diffusivity for three American coals. The diffusion parameter was shown to increase with increased average concentration of methane concentrations. Smith and Keller (1985) studied the effect of nonlinear adsorption upon the determination of diffusion coefficient using a single effective diffusivity model (unipore model), and noted that the magnitude of calculated sorption rate is different for the cases of nonlinear and linear adsorption, even though the sorption rate curve shape may be similar. Further, the effects of nonlinear adsorption may become particularly pronounced when large step changes in gas concentration are used during analysis. Bielicki et al. (1972) found a pressure-dependence of methane diffusivities. Clarkson and Bustin (1999) analyzed the pressure dependence of unipore and bidisperse effective diffusivities through comparing analytical and numerical models with experimental data, respectively. The diffusivities (both unipore and bidisperse pore) obtained with an analytical model (linear isotherm) increase with pressure, which is opposite to the results of numerical models (nonlinear isotherm). These also suggest that linear isotherm used in analytical model predicted wrong results.

**Matrix swelling and shrinkage**

As stated above, nonlinearity of sorption isotherm induce pressure- and concentration-dependence of diffusivity. Cui et al. (2004) suggested that other factors may also contribute to the pressure-dependence of apparent micropore diffusivity. Because the logarithmic value of apparent micropore diffusivity has a linear relation with pressure if intrinsic surface diffusivity ($D_0$) is constant. While they modeled diffusivities show much stronger pressure dependence. These factors may be adsorption swelling and coal matrix shrinkage. Adsorption swelling may narrow some micropore entrances and enhance the diffusion energy barrier of adsorbate in micropores, consequently reducing the diffusivities. The decrease of coal permeability is linearly related to gas (methane) adsorbed. The apparent diffusivity of CO$_2$ shows stronger pressure-dependence than CH$_4$ and N$_2$ especially at low pressure. This is consistent with the fact that the coal matrix swelling by CO$_2$ adsorption was found to be about five times that of CH$_4$.

**Multicomponent gas counter-diffusion in coal matrix**

Modeling multicomponent gas sorption kinetics is now an urgent requirement for ECBM project, especially the counter-diffusion process. However, few experimental and theoretical studies have been involved in this issue. Only two experiments are carried out on counter-diffusion process until now: (1) Reznik et al. carried out a set of experiments in which CO$_2$ was injected into 89-mm diameter large cores of CH$_4$- and CO$_2$- saturated bituminous coal at pressures of up to 5.5 MPa. (2) Wolf et al. reported a core flush test where CO$_2$ gas was injected into a large core to displace pre-adsorbed methane under controlled conditions. Four types of models have proposed to solve this problem:

- Different adsorbate diffusivity Clarkson and Bustin (1999) deduced different effective diffusivities for CH$_4$ and CO$_2$ ($CO_2 > CH_4$) through fitting unipore and bidisperse model with experimental data. Cui et al. (2003) also obtained same results, but they studied the selective adsorption and transport of gases (CO$_2$, CH$_4$ and N$_2$) from the point of adsorption affinity (energy) and kinetic diameter of gas molecules. Strong dependence of the diffusivity on gas species could have significant implications on gas production and CO$_2$ sequestration in coal seams. All of these results are obtained from single-component sorption kinetics experiments.

- Analytical solution for ternary gas system Zhu et al. (2002) described a new analytical theory of ternary gas flow for ECBM process. The multicomponent adsorption equilibria are approximated by extended Langmuir isotherm, and the gas phase behavior is predicted by the Peng-Robinson EOS. In addition, the analysis of Dindoruk was adopted for multicomponent gas flow with adsorption and desorption behavior.

- Concentration-dependent micropore diffusivity Shi and Durucan (2003) analyzed the effect of sorbate concentration on micropore diffusivity in their numerical simulation of a laboratory core flush test using a bidisperse model. They suggested that the test data cannot be matched with constant effective diffusivity, and then assumed a simple linear relationship between the micropore diffusivity and the total sorbate concentration, with which a good match has been achieved. However, this model assumed same diffusivities for CH$_4$ and CO$_2$ diffusion in coals.

- Maxwell-Stefan (MS) equation Fick’s law of diffusion is now the main method to describe coalbed gas diffusive process. For single-component gas, regardless of the flow mechanism that dominates gas transport in micropore system, the diffusion process obeys Fick’s law of diffusion. However, the multi-component gas diffusion can’t be described accurately using this approach. The Maxwell-Stefan equation can interpret the interaction of multi-component gas molecule occurring in coalbed gas diffusive process.

The MS diffusivity is commonly referred to as the intrinsic diffusivity while the Fick diffusivity is termed the apparent diffusivity. Further, Fick diffusivity shows a pronounced increase with surface occupancy. The MS diffusivity calculated from Fick diffusivity data is not constant. Krishna explained the reason is that with increasing surface coverage, the adsorbed species interact with each other causing a reduction in the MS diffusivity. Krishna (1990) employed Maxwell-Stefan equation to model multicomponent surface diffusion of adsorbed species. Wang and Bhatia (2001) also utilized this method for the prediction of single char particle gasification dynamics. However, The Maxwell-Stefan equation has not been used to model the counter-diffusion in coal seams.

**Inversion of Fick diffusivity**

Adsorption equilibrium parameters are relatively easy to obtain from batch equilibrium experiments. While the same may not be said for diffusion parameters, especially when there are two diffusion processes occurring within the system. The Fick diffusivity is generally determined through fitting experimental gas sorption data. Arvind and Bhatia (1994) mentioned four methods of estimating qualitatively diffusion coefficient:
Constant diffusive In most cases, the dependence is established by performing a series of differential runs, each at a different average gas concentration, involving small change in amount adsorbed. The resulting uptake curves are each fitted using a constant diffusivity model.

A priori form The uptake data are matched by assuming an arbitrarily chosen mechanism model of the surface diffusion have been attempted. It is proved that the uptake dynamics is relatively insensitive to the form of the assumed concentration dependence, so that discrimination among the diffusion models is not possible. Further, one can not rule out the possibility that a different model, not tested, will predict the uptake dynamics even more accurately.

Duda and Vrentas (1971) The concentration dependence of diffusivity was obtained without assuming its form a priori. However, the method was later found not suitable for analyzing experimental data due to the effect of errors involved in the uptake data.

Numerical solution, which is the most rigorous and exact approach so far. However, most of current numerical solutions are used for unipore diffusion system. Arvind and Bhatia (1994) deduced a numerical solution of concentration-dependent diffusivity from a single uptake curve using a combination of orthogonal collocation and regularization techniques.

Most of these inversion methods only work for unipore diffusion system. For diffusion occurring in multi-scale porous coal, bidisperse diffusion models can be used. Correspondingly the gas diffusivities can be determined by two methods described as follows.

Minimizing method, by which the apparent macropore and micropore diffusivities are usually retrieved as two fitting parameters by minimizing a least-square function.

Analytical method proposed by Do and Rice (1991) Under a given assumption, the contribution of pore diffusion and surface diffusion on overall sorption rate can be determined from a simple linear plot of the inverse of half time of adsorption verse a concentration factor. However, the analytical solution derived from Langmuir isotherm may be not accurate for any cases, especially for the cases of the poor fit of Langmuir isotherm to pure gas adsorption isotherms. Using this method, Karacan and Mitchell studied the surface and pore diffusivity of CO2 sequestration in coal seams, and reported that both of pore diffusion and surface diffusion are important for total sorption rate.

Water effects on gas transport in coal matrix

In 2001, Reeves and his colleagues found that to match water production history, the cleat porosity of a dual-porosity model has to be increased to unrealistic values. This indicates that the assumption of water only stored in large fractures (face and butt cleats) may be not necessarily accurate for some water-wet coals. Indeed in water-wet coals the small fracture system remains almost entirely filled with water, and gas sorption kinetics is determined by a slow diffusion process. The experiments carried out by Wolf et al. (2003) showed that in water-saturated coals water acts as a barrier, and the sweep efficiency is low for both gas phase and liquid carbon dioxide. However, supercritical carbon dioxide initially acts like liquid CO2, but after an apparent breakthrough it slowly improves in replacement of water and methane, and high sweep efficiencies are realizable.

These results are obviously important for the accurate evaluation of CO2 injection strategies for enhanced recovery of coalbed methane. However, the corresponding model studies are very limited. Currently most of matrix gas diffusion model are based on the assumption of dry coals, neglecting the effect of water on effective diffusion coefficients of methane and carbon dioxide. So far only the Mazumder et al. (2003) developed a model which can be used for describing water effects on binary gas diffusion (CH4-CO2).

To solve the problem of modeling water flow in matrix, as above stated, Reeves et al. (2001) proposed a triple-porosity/dual-permeability model to account for water effects on gas flow kinetics. This model extremely simplified the gas and water transport processes within coal matrix neglecting gas diffusion process in small fractures.

Mazumder et al. (2003) noted that in water-saturated coals gas diffusion occurs both in the gas phase and the liquid water phase. This means the effective diffusion rate depends both on the water saturation and distribution in the coal matrix. Since modeling this complicated process would severely hamper the application of the model, they assumed that all diffusive processes are effective diffusion in the gas phase. The effective diffusivity was defined as

$$D_{eff} = D_{l}S_{l} + D_{g}(1-S_{l})$$

Where, $D_{l}$ and $D_{g}$ are diffusion coefficients in liquid phase and gas phase respectively. $S_{l}$ is water saturation.

Variations in cleat porosity and permeability

The permeability of a coalbed is influenced during gas production by the simultaneous changes in effective stress, gas slippage and the volumetric strain of the coal matrix that is associated with gas adsorption/desorption. Although the changes in coal properties and its impact on the flow behavior of coal is an interesting phenomenon with a possibly significant impact on recovery of methane from coalbeds, the studies on this issue is very limited.

Independent effects of various Factors

The factors influencing cleat permeability and porosity during methane production were initially treated independently.

Effective stress

Many researchers studied the evolution of cleat permeability due to variation in stress and proposed several empirical equations based on analytical and experimental data. Among these, an exponential relationship of the form was reported by several researchers. Seidle et al. (1992) developed a relationship for permeability decline during depletion as a function of changes in stress, with which a collection of matchsticks geometry was extended to for a fractured coalbeds for testing against laboratory measurements, and excellent agreement was obtained.

Gas slippage
It has been proved that gas permeability in rocks of low permeability can be affected by the molecular, or Klinkenberg, slip phenomenon due to interaction between gas molecules and the flow path wall\textsuperscript{57}.

**Matrix volumetric strain**

Recently researchers reported that matrix shrinkage and swelling can cause profound changes in porosity and permeability of coalbed methane reservoirs during depletion or when under injection processes\textsuperscript{58-61}. Harpalani and Chen (1997)\textsuperscript{62} tried to evaluate the influence of matrix shrinkage by conducting permeability experiments at constant effective stress to ensure that the effect of matrix shrinkage can be isolated. The analysis is based on the assumption that the influences of matrix shrinkage and effective stress are independent, which might not be the case. The matrix shrinkage might result in a smaller reduction in the effective stress and thus even in an increase permeability. A better approach would, therefore, be to treat the two effects as coupled rather independent.

**Comprehensive effects of various factors**

The two effects of effective stress and shrinkage are not independent. The shrinkage of coal matrix with desorption may not only widen the cleats, but also reduce the effective horizontal stress. This would result in a reduction of stress across the vertical and sub-vertical cleats further opening these and increasing the permeability significantly\textsuperscript{63}. So far two kinds of approaches are used to model the coupled effects of the effective stress and matrix shrinkage and swelling: empirical formulas and coupled fluid flow with geomechanical deformation.

**Empirical formulas**

Two empirical formulas were proposed to describe the effects of matrix shrinkage and effective stress\textsuperscript{63, 64}. The first was developed by Advanced Resources International (ARI) for the COMET simulator and published in 1990 by Sawyer, et al. The second model was published by Palmer and Mansoori in 1996, and then P&M issued a revised edition of their publication in 1998.

Pekot and Reeves (2003)\textsuperscript{65} compared the two shrinkage models and concluded that the two models provide equivalent results for the most common CBM reservoir conditions. However, different results can be expected for reservoirs that are undersaturated or have unusual swelling behavior. For undersaturated coal reservoirs, the ARI model is based on gas concentration change, if no gas desorption occurs, no shrinkage occurs. While the P&M model is based on a change in the Langmuir strain relationship and appears to allow matrix shrinkage even when no gas is desorbed. Thus, the former appears superior for undersaturated CBM reservoirs. While in case where matrix swelling is not proportional to gas concentration, the P&M model is more accurate than ARI model by introducing a separate Langmuir strain function. If matrix swelling does not follow a Langmuir function, both models would be inaccurate.

**Coupled fluid flow and geomechanical deformation models**

Since the conventional models may give inaccurate predictions\textsuperscript{66-68}, more recent studies are focused on coupled modeling of fluid flow and coal geomechanical deformation during methane recovery\textsuperscript{66, 69}.

A few researchers have combined network flow models with limited degree of mechanical coupling. Seeburger and Nur (1984)\textsuperscript{70} developed a two-dimensional pore space model to investigate changes in permeability and bulk modulus of porous rock as a function of hydrostatic confining pressure. They applied Hagen-Poiseuille type expressions for flow through elliptic and tapered conduits with pressure dependent cross-sectional areas. The model did not allow irreversible deformation of the rock to occur.

Yale (1984) developed a three-dimensional network model and studied the effects of hydrostatic pressure on permeability and porosity, and how these are related to the geometric factors of the pores. All of these models have been based on the equivalent continuum approach. The main differences between the different models lie in the way the fractured medium is idealized and in the transport equations derived based on these idealizations.

Choi and Wold (1994) applied a discrete element model for coal which combines simple mechanisms of matrix deformation and discrete fracture network fluid flow to investigate stress change and stress-induced permeability alternation around the injection well during step rate injection tests. This model is a single-phase model, doesn’t include water flow. Lin et al. (2001)\textsuperscript{71} proposed a coupled model including water-gas flow equation and solid–deformation equation, and applied finite element method to disperse them.

Although the coupled models are superior to empirical formulas, it seems impossible now to model evolutions of coal cleat properties using a coupled model. The reason is that the relationship between fluid flow and geomechanics in coal seams is extremely complicated plus the gas adsorption and diffusion process that the coupled model would be too complicated to apply for engineering practice.

**Conclusions**

Extensive investigations both in laboratories and field pilots\textsuperscript{72, 9, 73, 41, 40, 74} show that existing CBM models do not correctly model mechanisms of the gas recovery process from coal seams, in particular the CO\textsubscript{2}-enhanced CBM recovery due to a lack of understanding of the physical and thermodynamic phenomena that occur when CO\textsubscript{2} is injected into a coal seam.

It is believed that multicomponent gas sorption/diffusion and sorption- and stress-induced coal permeability alteration are two remarkable aspects which have been improperly simplified in existing CBM models. Therefore, the two main issues should be addressed in future CBM/ECBM reservoir modeling\textsuperscript{5-7}.

Up to now most work is focused on the multicomponent adsorption equilibria. The experimental and theory studies on the multicomponent gases counter-diffusion through coal matrix are very limited. However, the competitive adsorption processes have been extensively studied by both experiment and numerical models. These approaches may be readily adapted to describe gas sorption kinetics in coalbeds.
Acknowledgments

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References


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<td>A little different</td>
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<tr>
<td>The adsorbent particle contains uniform radius microporous microspheres with the space between microspheres making up the macroporosity</td>
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<tr>
<td>Water effects on gas diffusivity</td>
<td></td>
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<tr>
<td>Inversion of gas diffusivities</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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</tr>
<tr>
<td>Two fitting parameters</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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</tr>
<tr>
<td>One parameter (micropore diffusivity)</td>
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Figure 1. Framework of existing gas diffusion models