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An alternative mechanistic model for permeability changes of coalbeds during primary recovery of methane

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Abstract

Volumetric shrinkage due to methane desorption from the coal matrix has significant influence on the stress regime and fracture permeability in coal. Permeability changes (due to primary depletion) up to two orders of magnitude have been reported from the Fairway region in the San Juan Basin. Several analytical models have been developed to predict changes in fracture permeability in coal as a function of stress and sorption induced coal swelling/shrinkage.

Coal can be considered as a highly crosslinked macromolecular network structure, where aromatic clusters of graphite like complexes are connected by aliphatic chains. All sorption processes in coal are characterized by relaxational mechanisms of such crosslinked complexes. Any relaxational mechanism is indicative of swelling related stresses in coal. Variations in the effective horizontal stresses under uniaxial strain conditions are effected as a function of the reservoir pressure reduction during primary drawdown, which includes a cleat compression term and a matrix shrinkage/swelling term that have opposite effects on fracture permeability.

The matrix shrinkage/swelling term have been revisited a theory proposed to explain the coupling of swelling stress to porosity change in coal as a function of the change in diffusion coefficient, the Langmuir constants, cleat compressibility and material properties.

Introduction

It is a known fact that permeability changes occur in coal as a result of both primary depletion and enhanced recovery processes associated with acid gas injection. In recent past all such changes in absolute permeability have been assigned to stress dependent cleat volume compressibility and sorption induced shrinkage or swelling of coal. Several analytical models have been developed in to predict the changes in the permeability of coal. A few selected references are as follows, Gray (1987), Harpalani and Schraufnagel (1990), Seidle and Huitt (1995), Palmer and Mansoori (1998), Gilman and Beckie (2000), Shi and Durucan (2005), Cui and Bustin (2005), Robertson and Christiansen (2005) and Pan and Connell (2007) presented a theoretical model to describe the volumetric strain associated with gas adsorption on coal, which was derived using an energy balance approach, assuming that the surface energy change associated with adsorption can be equated with elastic energy change of the solid. Clarkson et al. (2008) extended the Pan and Connell (2007) model for multicomponent system and incorporated it with the analytical Palmer and Mansoori (1998) model to match the field data on absolute permeability from the Fairway coals in the San Juan Basin.

In this paper an alternative mechanistic model has been presented to model permeability changes of coalbeds during primary depletion and secondary sequestration of acid gases. This model got inspired by the anomalous diffusion behaviour of coal in response to molecular relaxation associated with the interaction of acid gases and the macro-molecular network structure of coal.

There is a large amount of literature on anomalous diffusion, which already dates back to the sixties. Alfrey et al. (1966) have presented a second limiting case for sorption, where the rate of transport is entirely controlled by molecular relaxation. This type of transport mechanism is designated as Case II transport. Thomas et al. (1982) proposed that the rate-controlling step at the penetrant front is the time dependent mechanical deformation of the coal in response to the thermodynamic swelling stress. The Thomas and Windle model stimulated experimental research on Case II sorption, particularly by Lasky et al. (1988) and Gall et al. (1991) on a number of polymer / sorbent systems. Hui et al. (1987) dealt with both the initial transient penetration of the sorbent and the final

steady state motion of the sorption front - all within the framework of the Thomas and Windle model.

The question arises whether stress induced effects can sustain such an enhanced (proportional to time) super-diffusion process forever. Therefore we reviewed the modeling both from the physical as from the mathematical point of view. Mazumder et al. (2010) presented a shortened derivation of the equation originally derived by (Thomas et al. 1982) and rederived by Hui et al. (1987a and 1987b) with an emphasis on extended irreversible thermodynamics (Jou et al. 2001). Extended irreversible thermodynamics (EIT) differs from classical irreversible thermodynamics (CIT) by not only characterizing a volume element by thermodynamic variables (temperature, pressure, concentration), but also by its gradients. The mathematical analysis of the model is based on a dimensional analysis and a solution of the long-term behavior, using an analytical solution proposed by Sherwood and Pigford (Bird et al. 2002), which deals with an analytical solution that includes a sudden jump in diffusion coefficients. Mazumder et al. 2010 also analyzed a linearized version of the model.

Having said so the mass balance equation created an excellent framework where we could build our understanding around diffusive flux, adsorbate concentration, pressure, secondary porosity and swelling stress in both time and space. The “swelling” of coal by an adsorbate can be referred to as, an increase in the volume occupied by the coal as a result of viscoelastic relaxation of its highly crosslinked macromolecular structure. The principal point of departure from all other models is the specific considerations of the effects of the sorbent induced material misfit and the non-linear viscoelastic response of the constrained coal matrix to the misfit induced effective stresses. This stress is termed as the swelling stress (P_{xx}), and is defined as the pressure of an element of coal matrix saturated with the adsorbate (CH_4/CO_2) avoiding at the same time deformation. From the thermodynamics stand point, swelling stress represents a kind of energy required in the process of holding back a deformation by means of back compaction.

All relevant equations

The derivation included here is based on the article by Hui et al. (1987a, 1987b) and Landau and Lifschitz (1975), i.e. the molar flux J is not only driven by the volume fraction gradient $\partial\phi/\partial x$, but also by the stress gradient, $\partial P_{xx}/\partial x$ i.e.,

$$J = -D\phi \frac{\partial}{\partial x} \left(\ln \phi + \frac{\Omega}{k_B T} P_{xx} \right). \quad (1)$$

Where J is the diffusive flux, D is the diffusion coefficient, ϕ is the adsorbate concentration, Ω is the partial molar volume, k_B is the Boltzmann constant, T is the temperature and P_{xx} is the swelling pressure. The adsorbate concentration ϕ (kmol m^{-3}) can be written as follows (Langmuir Equation):

$$\phi = \phi_m bP / (1 + bP) \quad (2)$$

ϕ_m in the above equation is saturation constant of gas adsorption (mmol/g)

The second mass balance equation is as follows:

$$\frac{\partial \phi}{\partial t} + \frac{\partial J}{\partial x} = 0. \quad (3)$$

Making all the necessary substitutions we get,

$$\frac{\partial \phi}{\partial t} = \frac{\partial}{\partial x} \left(D\phi \frac{\partial}{\partial x} \left(\ln \phi + \frac{\Omega}{k_B T} P_{xx} \right) \right). \quad (4)$$

Permeability and cleat volume compressibility

The effective stress σ' for an under-saturated system is defined as $\sigma' = \sigma - \sigma_0 \chi$. The net stress σ [N/m^2] acts over the entire cross-sectional area under consideration, and the pore water pressure, σ_0 acts over the total area minus the solid-particle contact area. The effective stress is considered to be carried by the solid skeleton of a porous medium. χ is the Bishop's parameter [6], which is to be determined by experiments and has a strong non-linear relation to the saturation S , i.e., $\chi = \chi(S)$, $0 \leq \chi \leq 1$. χ becomes unity when the medium is saturated with water ($S = 1$).

For an under-saturated coalbed, the net stress is supported by the fluid pressure in the cleats and the swelling pressure, P_{xx} [N/m^2],

as a net effect of electrical repulsion and attraction between particles, i.e.,

$$\sigma = \sigma_0 \chi + P_{xx}. \text{ Thus } \sigma' = (\sigma - \sigma_0 \chi) = P_{xx}$$

Somerton et al. (1974) have shown that compressibility is unlikely to remain constant over the entire stress history. Instead it will approach the rock (or grain) compressibility as effective stress increases, because small asperities on the cleat face resist closure and must be deformed or crushed before further reduction in porosity. This results in a departure from linearity (constant pore compressibility). Note, however, that because compressibility is variable, average pore compressibility ($\bar{c}_p$) is also variable. For exponentially declining pore compressibility, $\bar{c}_p$ is given by

$$\bar{c}_p = \frac{1}{\sigma - \sigma_0} \int_{\sigma_0}^{\sigma} c_0 e^{-\alpha(\sigma - \sigma_0)} d\sigma = \frac{c_0}{\alpha \Delta \sigma} [1 - e^{-\alpha \Delta \sigma}],$$

Where α defines the rate of decline of pore compressibility as effective stress increases, c_0 is the pore compressibility at initial effective stress, σ_0 , and $\Delta \sigma$ is the increase in effective stress from σ_0 . For variable pore compressibility, $\bar{c}_p$ is not constant but simply represents the average pore compressibility over the stress interval ($\sigma - \sigma_0$). If σ changes the average $\bar{c}_p$ over the interval will also change. Thus assuming that the cleat compressibility declines exponentially with increasing stress, MaKee et al. (1988) derived the following stress permeability equation relationship by introducing a mean compressibility term,

$$k = k_0 \frac{e^{-3\bar{c}_p(\sigma - \sigma_0 \chi)}}{1 - por_i [1 - e^{-3\bar{c}_p(\sigma - \sigma_0 \chi)}]} = k_0 \frac{e^{-3\bar{c}_p(P_{xx})}}{1 - por_i [1 - e^{-3\bar{c}_p(P_{xx})}]} \dots\dots\dots(5)$$

where $\bar{c}_p$ is the mean cleat / fracture compressibility and is a function of stress. The mean cleat compressibility decreases with increasing stress and can thus be obtained by fitting experimental results.

Boundary conditions and Numerical solution

The typical distributions of pressure and swelling stresses during conventional CBM production are shown in Figures 1 and 2. These results indicate that pressures around the producer decrease (as expected) thus the mean effective stress increases. The distributions of pressure and effective stress also vary as a function of time and distance. As shown in Figure 2, during primary production of CBM, the pressures around the producer continuously decrease thus the effective stresses continuously increase until an economic limit is reached.

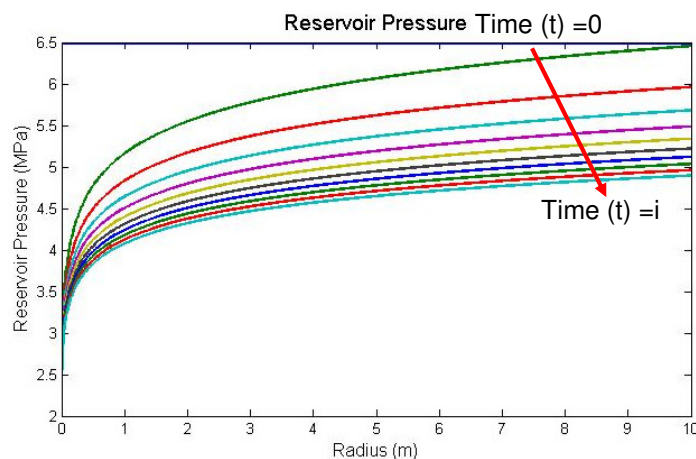


Figure 1 Reservoir pressure distribution around a CBM well on primary depletion

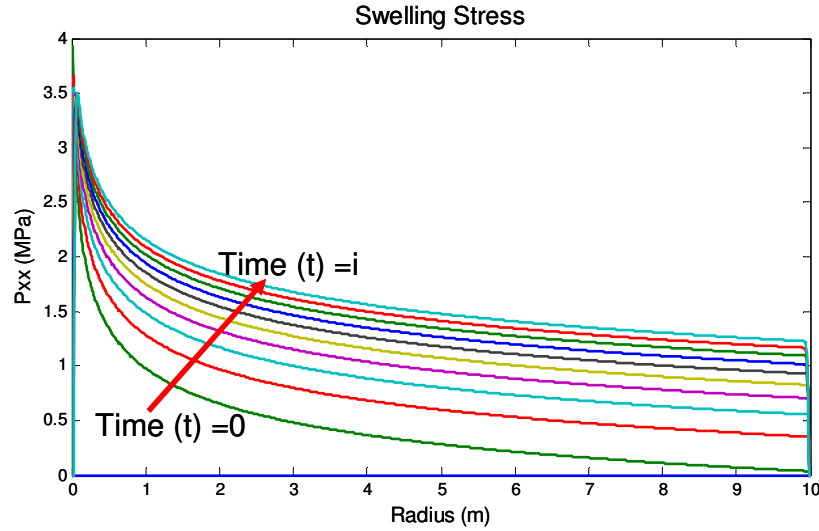


Figure 2 Swelling stress as a function of time and distance around a CBM well on primary production

The volume fraction of the sorbent in the coal is in equilibrium with the sorbent in the fluid phase outside the coal. Also the sorbent in the stressed coal is in equilibrium with the sorbent in the fluid phase. The final equilibrium volume fraction is reached when the coal has swollen to make the stress P_{xx} equal to zero. The change in chemical potential $d\mu = \Omega dP_{xx} + k_B T d \ln \phi$. Equating the chemical potential in the unstressed ($P_{xx}^{(0)} = 0$) and stressed state leads to:

$$\Omega P_{xx} + k_B T \ln \phi = \Omega P_{xx}^0 + k_B T \ln \phi_o.$$

where we used the initial condition $\phi = 0$ at $t=0$.

At $x = 0$ (which is at the well bore) and at $t = 0$, $P_{xx} = 0$. At $x = L$ there is a no flow boundary condition which means

$$\frac{\partial \phi}{\partial x} = 0 \text{ at } x = L$$

At $t = 0$ the curve representing the swelling stress, as shown in Figure 2 is a straight line with 0 to near zero values. With time as the well tends to drawdown the pressure profile changes as a function of time and distance.

The equations were solved using a finite different approach. For a given pressure profile we first calculate ϕ using Eq. (2), which just uses the reservoir pressure profile as function of time and distance to calculate the sorbed gas content as a function of Langmuir volume (ϕ_m) and Langmuir pressure ($1/b$). Then we discretize Eq. (4) in time and space and rearrange it to calculate the P_{xx} profile. The permeability changes are then calculated by using Eq. (5).

Parameters, Results and Discussions

The model is consistent with the fundamentals of stress dependent permeability in coal. It is known that permeability in coal which is highly stress dependent, declines exponentially with the increase in the confining stress as a result of compaction. In coal, at lower reservoir pressures the compaction in coal as a result of pressure depletion can largely be cancelled out by the effect of matrix shrinkage. Field evidences from the San Juan Basin as reported by Clarkson et al. (2008) do suggest the near exponential growth of permeability from a group of wells from the Fairway region of the San Juan Basin. This data is shown in figure 3.

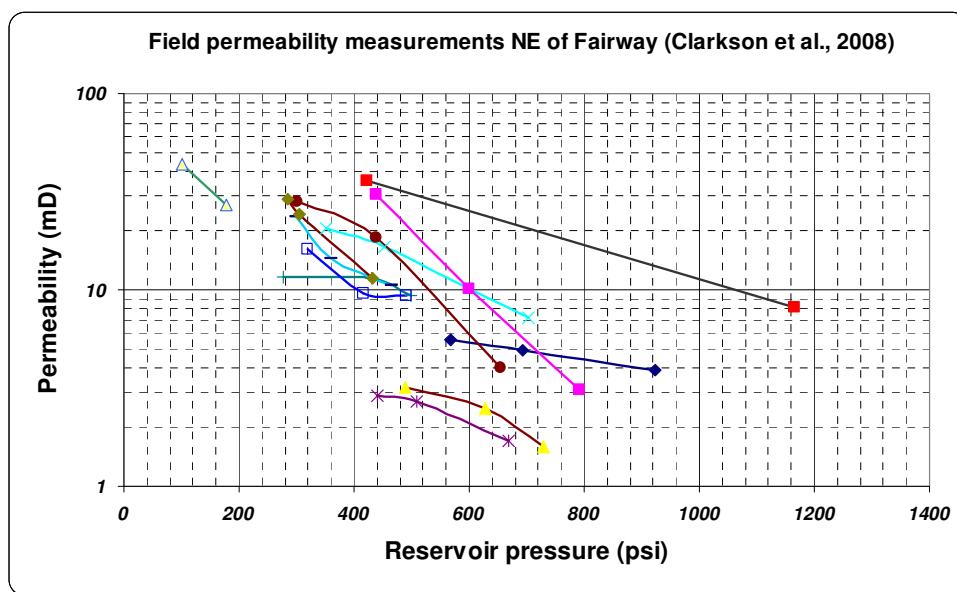


Figure 3 Field evidences from the San Juan Basin as reported by Clarkson et al. (2008) do suggest the near exponential growth of permeability from a group of wells from the Fairway region of the San Juan Basin

One of the wells (A-1) from the group of wells shown in Figure 3 was selected to try the model for a match for a reasonable set of input parameters. The parameters used to run the model for the match are shown in Table 1. The isotherm parameters are derived from the history matching done by Clarkson et al. (2008). The model results are shown in figures 4, 5 and 6. New insights have been gained with the model being tested for one set of parameters, to derive a match for the field data. Following which, additional improvements to the model input parameters are proposed.

All existing analytical models require additional material properties in terms of Young's modulus, bulk modulus, sorption induced strain, Poisson's ratio, surface and chemical potential etc. to predict permeability changes in coal as function of shrinkage and swelling in coal. With the mechanistic model all of the material properties have been rolled up into dynamic micropore diffusivity, Partial molar volume, mean fracture compressibility and Langmuir parameters for gas sorption. Most of these parameters can be measured as part of the standard adsorption experiments run during analytical testing.

Model Input Parameters		
Φ_m	0.627	mmol/g
$1/b$	200	psi
P_i	932	psi
k_0	3.85	mD
C_0	1.30E-03	psi ⁻¹
Por_i	0.005	[-]
D	1.50E-08	sec ⁻¹
T	45	°C
Ω	1.66E-27	m ³ /molecule

Table 1 Model input parameters used to match the field data from well A-1

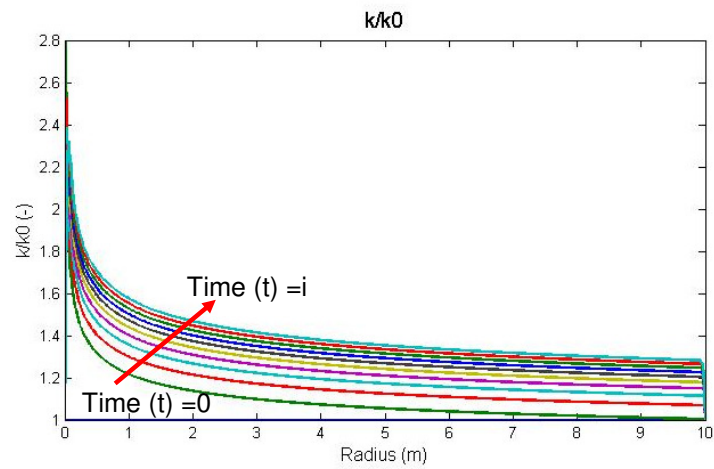


Figure 4 Model derived permeability ratio as a function of time and distance away from the well bore

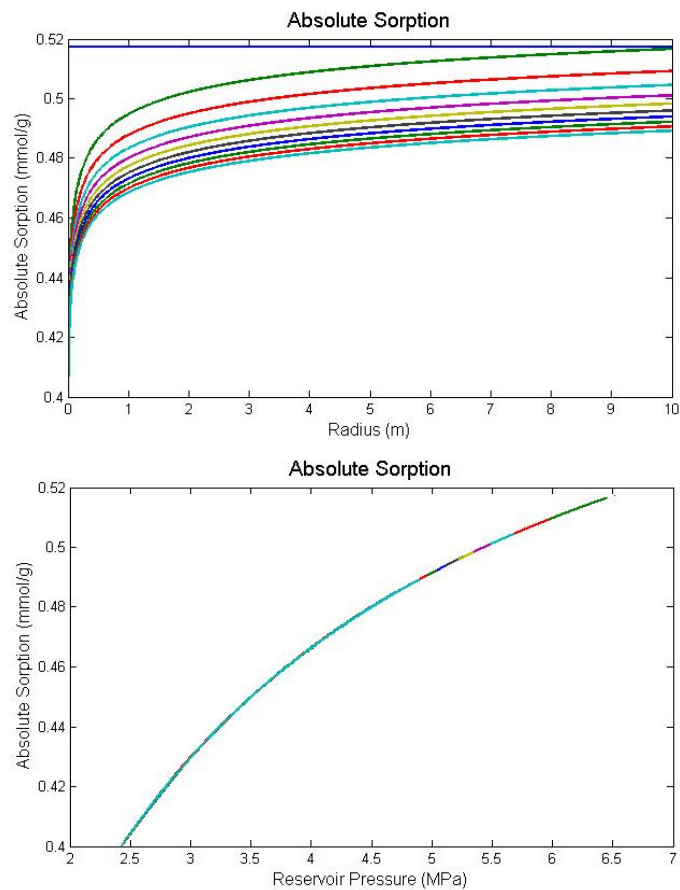


Figure 5 Model input for absolute sorption as a function of time, distance and reservoir pressure

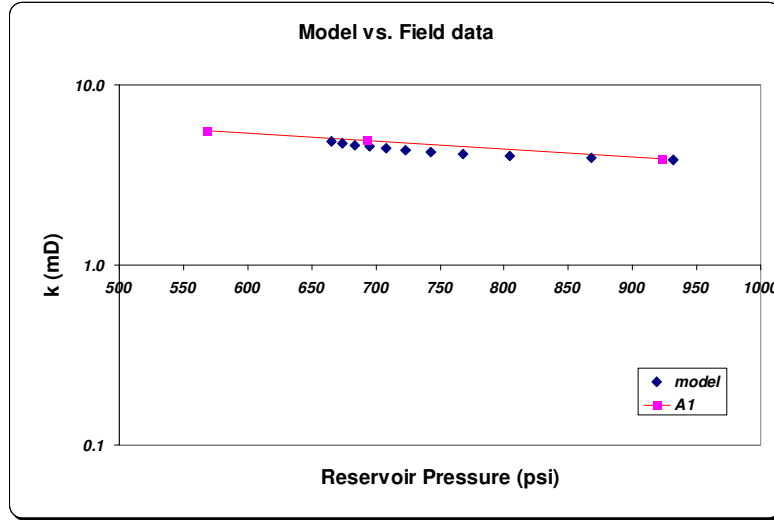


Figure 6 Comparison of the absolute permeability as predicted by this model and gas permeability obtained from the field. The initial permeability is equal to the permeability value estimated from field data at the initial reservoir pressure of 932 psi

Conclusions

- In summary the mechanistic model proposed here to predict perm growth is promising, but further work needs to be done, firstly to improve the model with all changes proposed below and secondly to constrain the match with more field data.
- It has been recognized (Zhu et al. 2002, Cui and Bustin, 2005) that gas diffusivities of CO₂, CH₄ and N₂ in coal are a function of the equilibrium sorption pressure. Both macro and micro pore gas diffusivities tend to decrease with gas pressure. As part of the model improvement, we would like to build in the dynamic diffusion coefficient as a function of the sorption pressure. Lennard Jones model can be used to model dynamic diffusivities of gases in coal.
- It is recognized that the partial molar volume of CH₄, CO₂ and N₂ in coal is a function of the reservoir temperature. More work needs to be done to better define that function.
- Effects of relative permeability will to be considered in the next version. Although the relative permeability effects become negligible below a certain pressure, it is absolutely necessary to understand the growth in the absolute permeability in conjunction with the effective permeability to gas.
- This model can easily be extended for a multicomponent system, by just adjusting the single component Langmuir parameters to a multi component one.

Symbols

Ω = Partial molar volume of adsorbate in coal; m³/molecule

k_B = Boltzmann constant; 1.3806503 x 10⁻²³ J/K

T = Temperature, °C

$\frac{1}{b}$ = Langmuir pressure (P_L); psi

P_i = initial reservoir pressure, psi

P_{xx} = swelling stress, psi

por_i = Initial fracture porosity; [-]

$\bar{c}_p$ = Mean cleat compressibility; psi⁻¹

ϕ_m = Gas sorption constant or Langmuir volume; [mmol/g]

D = Micropore diffusivity, m²sec⁻¹

L = radius away from the well; m

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