GEOLOGICA BELGICA (2004) 7/3-4: 123-127

RESERVOIR DEPLETION INDUCED CHANGES IN COALBED PERMEABILITY AND IMPLICATIONS FOR ENHANCED CBM RECOVERY USING CO_2 INJECTION

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(3 figures and 3 tables)

ABSTRACT. A model for describing changes in cleat permeability in a gas-desorbing coalbed under uniaxial strain conditions has been developed. An analysis on the possible behaviours of changes in effective horizontal stress (and thus cleat permeability) during reservoir drawdown is presented. The model has been applied to analyse the performance of three coalbed methane wells in the fairway of San Juan basin, USA, where continued increase in the absolute permeability has been observed during the course of primary recovery. The results of this study are presented and discussed.
The permeability model has been extended to account for matrix swelling as well as matrix shrinkage that are associated with multi-component gas adsorption/desorption, and therefore providing a first-order estimation on the permeability changes in coalbeds arising from CO_2 injection. Preliminary investigation has indicated that matrix swelling associated with CO_2 injection could have a detrimental impact on cleat permeability.

Keywords: Enhanced coalbed methane recovery, CO_2 sequestration, coal matrix shrinkage/swelling, permeability model

1. Introduction

Permeability of coal is recognised as one of the most important parameters for commercial coalbed methane production. Being normal to the bedding plane and orthogonal to each other, the face and butt cleats in coal seams are usually sub-vertically orientated. Thus changes in the cleat permeability can be considered to be primarily controlled by the prevailing effective horizontal stresses that act across the cleats, rather than the effective vertical stress, defined as the difference between the overburden stress and pore pressure.

The impact of increasing confining/triaxial stress on permeability of coal samples has been investigated by a number of researchers (Somerton *et al*., 1975; Durucan and Edwards, 1986). Experimental measurements indicated that permeability of coal decreases exponentially with increasing effective confining stress. Theoretical support for this exponential relationship was later provided by McKee *et al*. (1987) and Seidel et al (1992), based upon the assumption that the solid grains are incompressible.

Coal has been shown to shrink on desorption of gas and to expand again on resorption. During primary methane production, two distinct phenomena are known to be associated with reservoir pressure depletion, with opposing effects on coal permeability (Gray, 1987). The first is reservoir compaction which causes an increase in the effective horizontal stress. The second is gas (primarily methane) desorption from the coal matrix, resulting in coal matrix shrinkage and thus a reduction in the horizontal stress.

Gray (1987) was the first to incorporate the shrinkage effect into the estimation of effective stress within the coal to study the effect of reservoir pressure depletion on cleat permeability. In his formulation, coal matrix shrinkage is directly proportional to the changes in the equivalent sorption pressure (same as the reservoir pressure for gas saturated coal). However, recent studies (Harpalani and Chen, 1995; Seidle and Huitt, 1995) indicate that matrix shrinkage/swelling is proportional to the amount of desorbed/adsorbed gas, rather than to the sorption pressure change, as reported by earlier researchers. Given that non-linear Langmuir equations are widely used to describe gas sorption on coal, this implies that the effective stress, and thus the cleat permeability of coal, does not vary monotonously with declining reservoir pressure during drawdown. And indeed, there is field evidence which indicates strong rebound in cleat permeability during the course of primary recovery (Palmer and Mansoori, 1996).

A model for describing changes in cleat permeability in a gas-desorbing coalbed under uniaxial strain conditions has been developed in the current study. The present model is similar to Gray's model in that it incorporates the shrinkage effect into the estimation of effective stress within the coal. There is, however, an important difference between the two models: the volumetric matrix shrinkage in the present model is considered to be proportional to the volume of desorbed gas rather than to reduction in the equivalent sorption pressure.

During enhanced recovery/CO_2 sequestration in coal, adsorption of CO_2 gas, which has a greater sorption capacity than methane, may cause matrix swelling and thus, in contrast to gas desorption, could potentially have a detrimental impact on cleat permeability of coal. An extension of the present permeability model to account for matrix swelling as well as matrix shrinkage that are associated with multi-component gas adsorption/desorption is discussed.

2. Formulation of pore pressure-dependent permeability

Assuming constant overburden stress and uniaxial strain conditions in a producing coalbed, the change in the effective horizontal (principal) stress can be written as (Gray, 1987):

$$\Delta\sigma = -\frac{\nu}{1-\nu}\Delta p + \frac{E\Delta\varepsilon_s}{3(1-\nu)} \qquad (1)$$

where E and ν are the Young's Modulus and Poisson ratio of the porous rock, ε_S is the macroscopic volumetric matrix shrinkage strain induced by gas desorption from coal. Note that in Equation (1) compressive stresses are positive. The effective stress increment is related to the total stress increment $\Delta\tau_{ij}$ by $\Delta\tau_{ij} = \Delta\sigma_{ij} + \Delta p\delta_{ij}$, where p is pore pressure and δ_{ij} is the Kronecker delta.

As stated previously, recent studies (Harpalani and Chen, 1995; Seidle and Huitt, 1995) show that laboratory measured matrix shrinkage/swelling can be directly correlated to the amount of desorbed/adsorbed gas, rather than to the sorption pressure change. Langmuir isotherms are widely used to describe adsorption/desorption of methane in coal. Expressing the matrix shrinkage strain in Equation (1) using the Langmuir equation,

$$\varepsilon_S = \frac{\alpha_S V_L p}{p + P_L}$$

one obtains the following relationship for the changes in effective horizontal stress

$$\sigma - \sigma_0 = -\frac{\nu}{1-\nu}(p - p_0) + \frac{E\alpha_S V_L}{3(1-\nu)}\left(\frac{p}{p+P_L} - \frac{p_0}{p_0+P_L}\right) \qquad (2)$$

where α_S is the volumetric shrinkage coefficient, V_L and P_L are Langmuir parameters and subscript "0" refers to initial parameter values. Note that in arriving at Equation (2), it is implicitly assumed that 1) adsorbed gas is in equilibrium with free gas pressure in the cleats; and 2) the coalbeds are saturated with adsorbed gas at the initial reservoir pressure (p_0). Note that these two assumptions are not essential and can be relaxed. But they do lend to the analytical tractability demonstrated below.

Assuming a bundled matchstick geometry, it can be shown that cleat permeability is given by (Seidle *et al.*, 1992):

$$k = k_0 e^{-3c_f(\sigma - \sigma_0)} \qquad (3)$$

where c_f is the cleat volume compressibility with respect to changes in the effective horizontal stress normal to the cleat and k_0 is initial cleat permeability. The compressibility c_f is usually obtained by fitting Equation (3) to the laboratory permeability test data.

Equations (2) and (3) describe how permeabilities vary with pore pressure in a gas-desorbing coalbed under uniaxial strain conditions. The two terms in the right hand-side of Equation (2) are referred to as the cleat compression and matrix shrinkage terms respectively. As p is decreased from p_0, the cleat compression term is positive, while the matrix shrinkage term is negative. The magnitude of σ is therefore determined by the relative strength of these two opposing terms. A detailed analysis of how the horizontal stress changes as a coalbed is depleted is given in the following section.

3. Effective horizontal stress as a function of pore pressure

Define $f(p) \equiv \sigma_0 - \sigma$ (reduction in the effective horizontal stress) so that the cleat permeability varies positively with the stress function f. Let us now examine the properties of $f(p)$. Without loss of generality, a saturated coalbed is considered here. After some manipulation, the function f can be rewritten as

$$f(p) = \frac{\nu}{1-\nu}(p - p_0)[1 - \frac{E}{3\nu}\frac{\alpha_S V_L P_L}{(p+P_L)(p_0+P_L)}] \qquad (4)$$

Note that equation $f(p) = 0$ has a non-trivial solution ($p \neq p_0$),

$$p_{rc} = \frac{E}{3\nu}\frac{\alpha_S V_L P_L}{(p_0+P_L)} - P_L \qquad (5)$$

Also note that p_{rc}, which marks the point where the opposing effects of cleat compression and matrix shrinkage on the effective horizontal stress cancel each other out, is inversely related to the initial reservoir pressure p_0. The implication of this relationship will be discussed later. The term p_{rc}, the point at which the initial value of the effective horizontal stress is recovered, is referred to as the recovery pressure in this study.

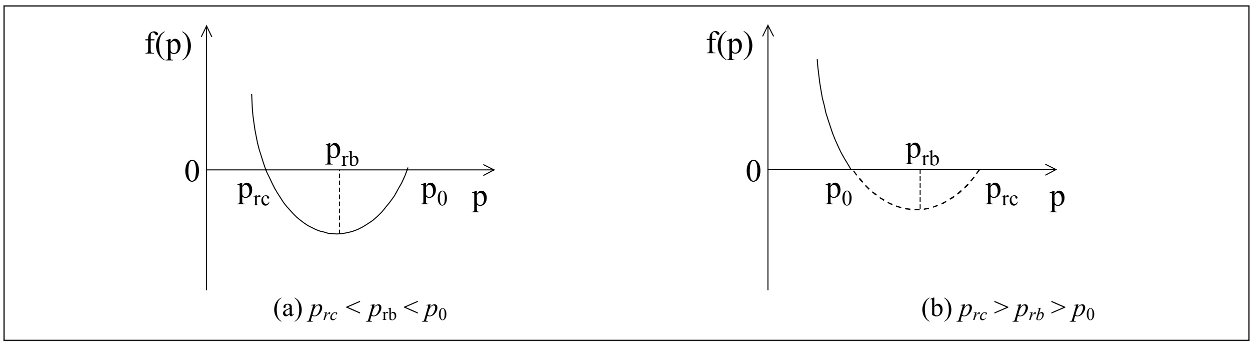

Figure 1. Schematic curves showing how change in effective horizontal stress varies with pore pressure during drawdown under different reservoir conditions.

It can also be shown that $f(p)$ has a minimum value at p_{rb},

$$p_{rb} = \sqrt{\frac{E\alpha_S V_L P_L}{3\nu}} - P_L \qquad (6)$$

Since p_{rb} marks the point where $f(p)$ rebounds, i.e., the effective horizontal stress decreases with further reservoir pressure reduction, it was referred to as the rebound pressure by Palmer and Mansoori (1996). It is noted that p_{rb} is independent of p_0.

Based upon the above analysis, a qualitative description of function $f(p)$ can now be given. There are three possible scenarios depending on the magnitude of p_{rc} relative to p_0:

$p_{rc} < p_0$: As p is reduced, $f(p)$ experiences a transition from being initially negative ($\sigma > \sigma_0$) to positive ($\sigma < \sigma_0$) when p is reduced below p_{rc}, Figure 1a. Note that p_{rc} could be less than zero if the matrix shrinkage term is weak.

$p_{rc} > p_0$: In this case $f(p)$ is always greater than zero ($\sigma < \sigma_0$) as p is reduced (Figure 1b). It can be further demonstrated that $f(p)$ increases monotonously with decreasing p ($f'(p) < 0$).

4. Model application to field data

Field evidence demonstrating increased reservoir permeability with continued gas production has been reported by Mavor and Vaughn (1997). Well tests carried out at three wells in the Valencia Canyon area of the San Juan Basin recorded absolute permeability increases ranging from 2.7 to 7.1 times the original permeability value. The well test results are presented in Table 1, together with the initial reservoir pressure at the three wells.

Using the pore-pressure dependent permeability curve shown in Figure 2 (dashed curve), Mavor and Vaughn succeeded in history matching the production data at wells VC 32-1 and VC 32-4. Since a history matched pore pressure-permeability relationship reflects the response of the coalbed reservoir permeability to drawdown, we

	VC 29-4	VC 32-1	VC 32-4
p_0 (MPa)	5.35	6.60	6.41
p/p_0	0.46	0.55	0.41
k/k_0	4.09	2.72	7.07

Table 1. Well test results showing increased permeability at the Valencia Canyon area (after Mavor and Vaughn, 1997).

υ	0.30
E (MPa)	2900
P_L (MPa)	2.55
$\alpha_S V_L$	0.013
c_f (MPa^{-1})	0.290 (0.266 for VC 29-4)

Table 2. Well test history match data for the Valencia Canyon wells (after Mavor and Vaughn, 1997).

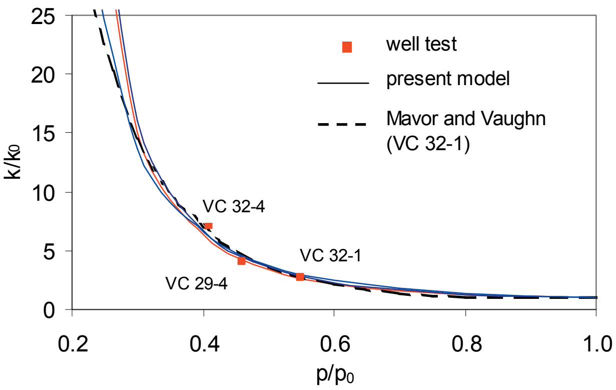

Figure 2. Published San Juan basin permeability response curve and model predictions.

shall henceforth refer to such a relationship as the pore pressure (reservoir pressure) dependent permeability response curve (or simply permeability response curve) of a coalbed reservoir. Using the reservoir parameter values representative of the San Juan basin coalbeds (Table 2) as model input, the model presented in this paper was able to match the permeability response curve at all the three wells, Figure 2.

5. Impact of matrix swelling on coal permeability

When CO_2 gas is injected into a coalbed, coal matrix swelling caused by CO_2 adsorption may overcome the pore pressure effect associated with injection and potentially have a detrimental impact on coalbed permeability. Field evidence suggests that the well injectivity has indeed declined at the early stages of CO_2 injection and then rebounded at the Allison pilot in the San Juan Basin (Reeves, 2002). In this section, the permeability model presented in section 2 is extended to account for matrix swelling as well as matrix shrinkage that are associated with multi-component gas adsorption/desorption, and therefore providing a first-order estimation on the permeability changes in coalbeds arising from CO_2 injection. Equation (2) may be rewritten as

$$\sigma - \sigma_0 = -\frac{\nu}{1-\nu}(p - p_0) + \frac{E\alpha_S}{3(1-\nu)}[C(p) - C_0] \qquad (7)$$

where $C(p)$ is the adsorbed gas concentration at reservoir pressure p, and C_0 the initial adsorbed gas concentration. Assuming that coal matrix shrinkage/swelling associated with desorption/ adsorption of a gas mixture is proportional to the net amount of gas desorbed/adsorbed and that sorption equilibrium is reached instantly, Equation (7) may be expanded, for a n-component gas mixture, to

$$\sigma - \sigma_0 = -\frac{\nu}{1-\nu}(p - p_0) + \frac{E\alpha_S}{3(1-\nu)}\left(\sum_{j=1}^{n} C_j - \sum_{j=1}^{n} C_{j0}\right) \qquad (8)$$

where C_j is the adsorbed gas concentration for component j, and is given by

$$C_j = \frac{V_{jL} p_j / P_{jL}}{1 + \sum_{j=1}^{n} (p_j / P_{jL})} \qquad (9)$$

where V_{jL} and P_{jL} are Langmuir parameters for gas component j and p_j is the partial free gas pressure, $\sum p_j = p$. Equation (9) is the extended Langmuir isotherm, which is used due to its simplicity. There is laboratory evidence that other isotherm models, such as the two-dimensional equation-of-state and ideal adsorbed solution (ISA) models, are more accurate than the extended Langmuir model in describing binary gas sorption in coal. However, it is believed that the extended Langmuir equation is adequate for the current purpose, i.e., to provide a first approximation on the changes in cleat permeability during enhanced CBM recovery.

5.1. An illustrative example

Utilizing Equations (8) and (9), together with equation (3), a preliminary study was carried out to illustrate the potential impact of matrix swelling on coalbed permeability arising from injecting CO_2 into coalbeds. Table 3 lists the values of the parameters used, which are representative of the San Juan basin coalbed reservoirs. Note that the values of maximum shrinkage/swelling strain ($\alpha_S V_L$) in Table 3 are for pure gases, whereas those given in Table 2 were obtained from history matching the field permeability data, where a CO_2 concentration of around 10% was reported in the produced gas stream. Also note that a lower cleat compressibility c_f of 0.145 (compared to 0.290 in Table 2) is used here to reflect an average well.

The estimated changes, with total reservoir pressure for a given composition of CH_4-CO_2 mixture in the cleats, in the effective horizontal stress and permeability are presented in Figure 3a. It is assumed that the free gas phase in the virgin coalbed consists of 90% CH_4 and 10% CO_2. The impact of increasing CO_2 concentration in the cleats on coalbed permeability is clearly demonstrated in Figure 3b. The results indicate that, in this particular case, the coalbed would experience an almost two orders of magnitude reduction in permeability if it is saturated with CO_2 at the initial reservoir pressure.

p_0 (MPa)		10.34
υ		0.30
E (MPa)		2900
P_L (MPa)	CH_4	2.55
	CO_2	1.64
$\alpha_S V_L$	CH_4	0.0116
	CO_2	0.0182
c_f (MPa^{-1})		0.145

Table 3. Model input for a CH4-CO2 binary gas mixture.

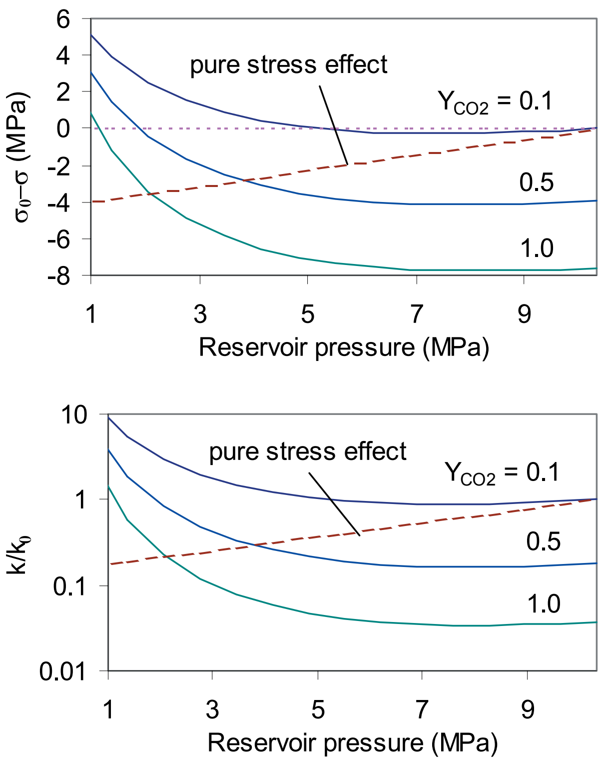

Figure 3. Estimated changes in the coalbed permeability with CO_2 injection (above) effective horizontal stress; (below) cleat permeability.

6. Conclusions

A model for describing changes in cleat permeability in a gas-desorbing coalbed under uniaxial strain conditions was developed. An analysis of the possible changes in effective horizontal stress (and thus cleat permeability) during reservoir drawdown is presented. When applied to three Valencia Canyon coalbed wells in the San Juan Basin, where increased absolute permeability during gas production has been observed, the model predictions are in good agreement with the published pore pressure dependent permeability changes.

The permeability model has been extended to account for matrix swelling as well as matrix shrinkage that are associated with multi-component gas adsorption/desorption, and therefore providing a first-order estimation on the permeability changes in coalbeds arising from CO_2 injection. Preliminary investigations into the potential impacts of matrix swelling associated with CO_2 injection on coalbed permeability indicate that the permeability could be reduced by two orders of magnitude when fully saturated with CO_2.

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Manuscript received 5.11.2002 and accepted for publication 14.3.2003.