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Numerical prediction of *in situ* horizontal stress evolution in coalbed methane reservoirs by considering both poroelastic and sorption induced strain effects

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ABSTRACT

As an organic-rich dual-porosity medium, coal distinctively manifests unique deformation and permeability evolution behaviors due to the adsorption/desorption induced matrix swelling and/or shrinkage. Being different from the elastic strain, the sorption induced strain shows a non-linear behavior with continuous sorbing gas injections, and these two types of strains are competing process of the volumetric change for coal. With primary gas depletion, the horizontal stress decreases within coalbed methane (CBM) reservoirs due to the *in situ* boundary confinement, namely, uniaxial strain boundary condition. However, the coal solid skeleton deformative behavior with primary depletion is not specifically clear due to the difficulty both in field and lab measurement of horizontal stress. This paper, based on a gas-solid coupling model incorporated with swelling effect, focuses on the horizontal stress variation with respect to the primary depletion under uniaxial strain condition. It was found the simulated results of volumetric change under the hydrostatic condition well agree with experimental data. The increase of horizontal stress for methane is four times as for helium, with injected pore pressure at 7.6 MPa. Also, the conceptual dual-material model is proposed to demonstrate the competing process of compression and swelling, which leads to the bulk modulus change of coal. It was found the Biot's coefficient can be larger than unity and be a variable during the primary depletion due to the swelling induced equilibrium negative bulk modulus.

1. Introduction

Coalbed methane (CBM), as an increasingly prevalent unconventional gas resource, has been extensive extracted in U.S. during the past four decades. Notably distinctive with conventional gas reservoirs, methane in coal is not structurally “trapped” by overlying seals. Instead, the majority of the gas is contained within the coal in the form of adsorbed gas on the internal pore surfaces of coal matrix.[1] With the primary production by reservoir pressure depletion, the adsorbed gas gradually desorbs from the coal matrix which results in a matrix deformation – an overall matrix shrinkage.[2–5] Under the *in situ* subsurface condition, the matrix shrinkage could lead to a net aperture opening of the pre-existing fractures (termed as cleats for coal) with pressure depletion.[6,7] With the progressively enlarged cleats aperture, the permeability of coal increases with gas depletion. This permeability increase has been confirmed through the field observation,[8–10] replicated laboratory measurements[11–15] and theoretical modeling analysis.[11,16–22]

Most recently, the matrix shrinkage has been claimed to be one of the driven forces for formation geomechanical failure and coal fine production in San Juan CBM fields.[23] The root reason for this formation failure was the increase of deviatoric stress at late production stage due to the excess desorption-induced horizontal stress loss.[24,25] Under *in situ* geological constrains, CBM reservoirs, assumed to be infinite in extent with a comparatively thin vertical seam thickness, will experience a reduction in reservoir pressure with continued production, which, in turn, results in the relaxation of stress within and surrounding the reservoir. This phenomena, typically, has been observed at conventional oil and gas production fields with a remarkable reduction of lateral stress while a negligible reduction in vertical direction.[26,27] It is noteworthy that horizontal stress here usually refers to minimum horizontal

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stress change ($\triangle\sigma_{H\ \min}$).

A sound knowledge of stress relaxation during gas depletion within CBM reservoirs and prediction of induced stress change prior to production are vital for CBM wellbore stability analysis, optimization of long-term gas production planning, enhanced recovery operations, as well as evaluation of faulting reactivation and fracture evolution.[24] This article aims at establishing a coupled sorption-geomechanical model to simulate the horizontal stress evolution under *in situ* CBM reservoir boundary condition. The coupled model links the sorption induced matrix shrinkage to geomechanial stress evolution through modified poroelastic constitutive governing equation. The modeled results well agree with *in situ* experimental measured data. Finally, the influence of Biot's coefficient on the horizontal stress evolution during depletion was discussed in detail.

2. Background and previous studies

Based on plane strain elastic equations, Olson[28] proposed the horizontal stresses estimation at depth by combining the effects of gravitational loading, tectonic, and thermal components and the minimum horizontal stress is given as follows:

$$\sigma_{h\ \min}^{0} = \frac{\nu}{1-\nu}\sigma_v + \frac{E}{1-\nu^2}\varepsilon_{tect} + \frac{E}{1-\nu}\alpha_T\Delta T \tag{1}$$

where E is the Young's modulus, ν is the Poisson's ratio, ε_{tect} is the horizontal tectonic strain which is assumed to remain uniform with depth, α_T is the linear elastic thermal expansion coefficient of the rock, and ΔT is the increase in temperature. Eq. (1) defines the initial state of stress for a subsurface reservoir, but it lacks the ability to describe the dynamical change of horizontal stress with either pressure depletion or temperature fluctuation. As a matter of fact, the horizontal stress changes with continuous pressure depletion and its variation is the most important parameter for the geomechanics characterization in the energy exploitation and waste fluid subsurface disposal. In this study, we only concentrated on the pressure depletion induced horizontal stress evolution for sorptive CBM reservoirs.

2.1. Reservoir horizontal stress change with pressure depletion

Considerable research efforts have been devoted over the last fifty years to characterize and predict the horizontal stress evolution with formation pressure drawdown. Both field and laboratory investigations have demonstrated that the minimum horizontal stress linearly decrease with pressure depletion for conventional petroleum and gas formations.[27] However, the horizontal stress profile of CBM reservoirs with depletion has not been fully understood due to the complex sorption-induced stress-strain relationship.[14,15,24] With a pressure drawdown in conventional reservoirs, only pressure/stress induced strain occurs and impacts the horizontal stress. However, for CBM reservoirs, in addition to the pressure/stress induced strain, there is a thermodynamic-driven sorption induced strain which will lead to an excess stress loss with the same pressure drawdown.[29] Essentially, the sorption induced strain needs to be quantified. Fortunately, the sorption induced strain has been measured and studied.[1,2,4,21,30–34] A non-linear relationship between strain and pore pressure is demonstrated in these studies.

Followed this, the horizontal stress profile for coal was measured under best replicated *in situ* condition by Mitra et al.[13]. They conducted the methane depletion experiment using cylindrical coal sample, and the experimental results indicate the horizontal stress linearly decreased with methane pressure depletion. Interestingly, the horizontal stress loss is more than the methane pressure decrease in order to maintain the uniaxial strain condition and this stress loss was termed as "*excess horizontal stress loss*". This was believed to be due to the sorption induced strain.[24] Subsequently, Liu and Harpalani[24] conducted both helium, known as non-sorbing gas, and methane depletion experiments. The results showed that the coal reservoir behaves somewhat similar to the conventional reservoirs with helium depletion at which the horizontal stress loss is less than the decrease of pore pressure. However, the amount of horizontal stress loss exceeds the pore pressure drawdown with methane depletion. Similarly, Espinoza et al.[25] carried out a series of triaxial experiments to measure horizontal stress with CO_2 depletion and the results indicate that a larger decrease of horizontal stress may occur in CBM reservoirs than conventional gas reservoirs.

2.2. Numerical simulation evolution in ad/desorption-induced deformation

Numerical simulations have been extensively used to define the geomechanical responses involving multi-physics of fluid-rock interactions. Generally, finite element method coupled with fluid-solid interaction is employed. By taking diffusion into consideration, Valliappan and Zhang[35] acquired a nonlinear partial differential governing equation. To evaluate the flow-deformation effect for cylindrical laboratory samples during injection, Bai et al.[36] extended a dual-porosity poroelastic model and used it to simulate the behavior of homogeneous and heterogeneous laboratory specimen under triaxial injection conditions. However, most of these above models are based on the stress-strain constitutive similar to conventional poroelastic mechanics and the effect of adsorption-induced strain on matrix has not been specifically discussed although this effect has a dominant influence on the evolution of horizontal stress and permeability which has been noted by numerous experimental data. Taking sorption-induced strain into account, Palmer and Mansoori[33] developed an analytical function to describe the porosity and permeability evolutions in coal. Espinoza et al.,[25] however, pointed out that Palmer and Mansoori model may get a questionable result under uniaxial strain conditions in CBM reservoirs.

As aforementioned discussions, the sorption induced strain is a unique feature for sorptive coal medium and it should certainly be considered in the stress-strain constitutive relationship during the geomechanical modeling. This article, hence, develops a new flow–-deformation coupled model incorporating sorption-induced matrix strain and the established model was validated by our previous published experimental results.

3. Proposed numerical model: theories and model development

3.1. Assumptions of proposed numerical model

Distinguishing from conventional poroelastic materials, desorption/adsorption induced matrix shrinkage/swelling should be considered when we calculate the bulk deformation of a CBM reservoir. Thus, the coal deformation is defined by mechanical induced deformation determined by gas pressure and external applied stress and matrix sorption-induced deformation. The superposition principle is employed in this coupling model to estimate the overall deformation due to gas depletion. Based upon the poroelastic principles, the following assumptions are applied to deformative CBM reservoirs: (a) coal is a transversely isotropic porous medium; (b) strains are much smaller than the studied length dimension; (c) ideal gas law is valid within the pores of the coal and; (d) Darcy's law is valid for gas flow through the coal cleat network.

3.2. Constitutive law and governing equations

The Biot model assuming a coherent solid skeleton and a freely moving pore fluid for a fluid-filled porous material denotes that the strain quantities are related to the usual small strain tensor ε_{ij},[37] where a positive ε_{ij} represents extension, and the strain quantities are expressed as: