Geomechanical aspects of coalbed methane production : Flow model formulation

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RÉSUMÉ. *La plupart des charbons contiennent des quantités relativement importantes de méthane, représentant une source énergétique certaine. Cependant, le charbon n'est pas un réservoir conventionnel et les outils de modélisation classiques s'avèrent inefficaces pour modéliser l'exploitation du méthane dans un tel réservoir. Un point crucial est la capacité du modèle à représenter l'évolution de la perméabilité due aux couplages hydro-mécaniques en cours de production. Cet article présente deux modèles poursuivant un même objectif : modéliser le comportement hydraulique du charbon. Il y a d'une part un modèle macroscopique utilisant un double continuum pour représenter la structure particulière du charbon et d'autre part un modèle microscopique pouvant servir de base à une approche multi-échelle. Dans les deux cas, la perméabilité est exprimée en terme d'ouverture de fracture en vue de faciliter les couplages avec un modèle mécanique.*

ABSTRACT. *Most coals hold important quantities of methane which represents a significant source of energy. However, coal reservoir is not conventional and classical tools are inadequate for the modelling of methane exploitation in this kind of reservoir. They improperly simplify the geomechanical processes involved. A critical issue is to correctly model the permeability changes due to hydro-mechanical couplings during methane production. This article presents two different approaches with the same objective: modelling the hydraulic behaviour of coal. Firstly, we present a macroscopic approach with a double continuum to take into account the particular structure of coal and secondly, a microscopic approach which may serve as basis for a multi-scale approach. In the two cases, the permeability is expressed with the fracture aperture width to facilitate the further coupling with a mechanical model.*

MOTS-CLÉS : *Gaz de charbon, géomécanique, modèle hydraulique, macroscopique, microscopique*

KEYWORDS: *Coalbed methane, geomechanics, hydraulic model, macroscopic, microscopic*

1. Introduction

Methane can be found almost anywhere there is coal because it is part of the genesis of coal. Considered as the miner's curse, coalbed methane (CBM) is now recognized as a valuable fuel since the "energy crisis" of the 1970s [FLO 98]. As coal sourced the gas it holds, this gas resource is referred as unconventional. Moreover, coals are naturally fracturated reservoirs, its fractures are termed cleats. There are generally two sets of orthogonal opening-mode fractures, it delimits small blocks (Figure 1) [LAU 98]. The cleat system is important for the CBM production, it is the principal permeability pathway for water and gas during production. Permeability is affected by the geometry of the cleat system : spacing and height, aperture width and connectivity [CLA 97]. Despite coal is mined for many centuries, the study of flows through this particular porous medium is explored recently in the history of coal. It is now of great interest to improve the CBM production efficiency.

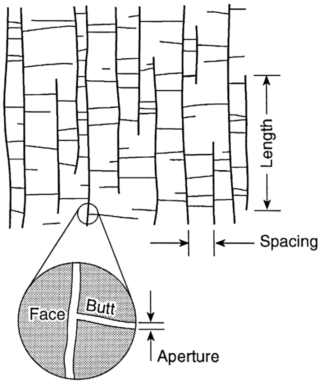

Figure 1. *Schematic cleat system, from [LAU 98].*

Coal is a dual porosity system made of matrix blocks and cleats. The cleat system has a low storage capacity and high fluid transmissibility while the matrix system has a low fluid transmissibility but a high storage capacity. Indeed, micropores serve as the storehouse for large quantities of methane held by an adsorption mechanism [HAR 90]. Hence, CBM production consists to desorb gas molecules from the internal surface of coal.

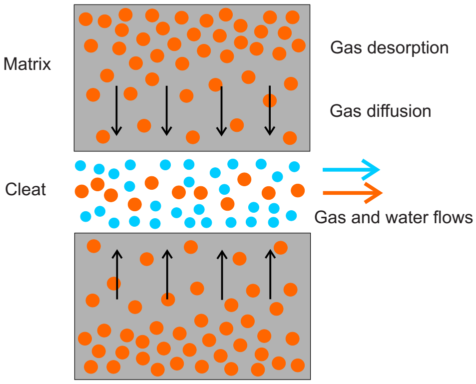

Figure 2. *Migration processes.*

Coal deposits are usually aquifers, coal cleats are initially water saturated for most of the reservoirs. In general, it is therefore the hydrostatic pressure that holds the gas adsorbed in the coal matrix. Production of CBM consists first to mobilize water in the cleats to reduce the reservoir pressure. This reduction of pressure in the coal seam is followed by the desorption of methane from the matrix. Gas molecules then diffuse through the matrix, migrate through the cleat system, and finally reach the wellbore or the mine shaft (Figure 2) [MOO 12].

Cleats contain minor amounts of free gas but they are responsible for fluid flow from the reservoir to the well and any element affecting the cleat network will impact the reservoir permeability. In particular, two distinct phenomena are known to be associated with reservoir pressure depletion, which have opposing effects on coal permeability [GRA 87]. The first phenomenon is the reservoir compaction due to the increase in the effective stress after the reservoir depletion. It tends to decrease the permeability. The second is the matrix shrinkage following the gas desorption from the coal. It increases the cleat permeability.

Moreover, the recovery of coalbed methane can be improved by stimulation treatment as hydraulic fracturing or CO_2 injection. Carbon dioxide has a higher affinity for coal and thus displaces methane locked within the coal. However, coal may swell with the resorption of CO_2, what could have a detrimental impact on the permeability [SHI 06].

As one can observe, coal properties may change during CBM production, it is crucial to know how it impacts the productivity. Different scenarios may be assessed through the modelling. This article presents a mathematical hydraulic model with two different approaches, macroscopic and microscopic. Both approaches are based on the mass balance of flow and storage rates in multi-phase conditions, it is described hereafter.

2. Hydraulic model

The hydraulic model is based on Reynolds transport theorem[1] : flows and storage rates are balanced for each species, gas and water. In the coal matrix, the rate of variation of the gas storage corresponds to adsorption or desorption of gas molecules, a storage model for sorption is presented in section 2.1. Concerning the flux, equations modelling the diffusive gas flow in the matrix and viscous two-phases flow in the cleats are described in section 2.2. Thence, balanced equations are presented in section 2.3.

2.1. *Storage model for sorption*

Adsorption isotherm is the most widely used technique to describe gas adsorption, providing a curve that gives the quantity of adsorbed gas as a function of gas pressure at a given temperature. The Langmuir model [LAN 18] is extensively used for describing methane adsorption/desorption on coal because of its ability to close fit experimental data. The shape of the Langmuir isotherm is presented in Figure 3, the equation writes as follows :

$$V_{g,Ad} = \frac{V_L \cdot p}{P_L + p} \tag{1}$$

where V_L $[m^3/kg]$ is the maximum adsorption capacity and P_L $[Pa]$ is the Langmuir pressure corresponding to $\frac{1}{2}V_L$. In fact, $V_{g,Ad}$ and V_L are not strictly volumes but volumes of stored gas in standard conditions per unit of mass of coal.

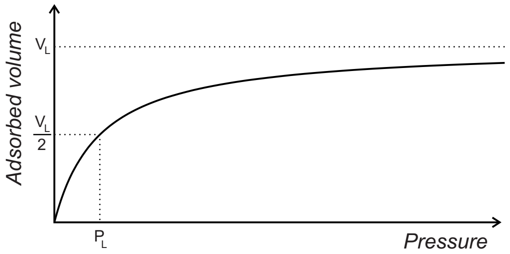

Figure 3. *Langmuir isotherm.*

The density of the gas adsorbed on the coal matrix is then evaluated as :

$$\rho_{g,Ad} = \rho_c \cdot \rho_{g,std} \cdot V_{g,Ad} \tag{2}$$

where ρ_c $[kg/m^3]$ is the coal density and $\rho_{g,std}$ $[kg/m^3]$ is the gas density at standard conditions. Note that $\rho_{g,std}$ is used precisely to overcome the standard conditions. Thence, expression (2) for $\rho_{g,Ad}$ is valid under the pressure p et temperature T used to calculate $V_{g,Ad}$.

In fact, the isotherm should be read as the maximum gas storage capacity at a given reservoir pressure instead of the gas content. Indeed, in presence of aquifers, the gas content is maintained trapped by the hydrostatic head

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[1] The sum of the changes of an intensive property defined over a control volume must be equal to what is lost/gained through the boundaries of the volume plus what is created/consumed by sources and sinks inside this volume.

of water, what represents a point under the Langmuir isotherm since the water pressure increases the gas storage capacity but not the gas content.

2.2. *Flow model*

In physics, the motion of compressible Newtonian fluids is described by the Navier-Stokes equations. Solving a flow problem with the Navier-Stokes equations is a *direct modelling* approach, *i.e.* the physics is directly solved. This approach requires the detailed geometry of the medium and the fluid properties (viscosity and density) as inputs. In porous media, flow occurs in the pore spaces between the solid skeleton. In this case, the description of the geometry is complex and the pore-scale representation is not suitable to simulate flow over large domains. Hence, a *phenomenological* approach is generally preferred with the Darcy's law.

From the experiments performed by Darcy on a column of sand [DAR 56], it follows that the flux q $[m/s]$ through a porous medium is proportional to the total pressure drop. This law is valid at small Reynolds numbers. In one dimension, it writes :

$$q = -\frac{k}{\mu}\frac{\mathrm{d}p}{\mathrm{d}s} \tag{3}$$

where s is the distance in the one-dimension system[2]. In equation (3), k $[m^2]$ is called the *intrinsic* or *absolute permeability* of the porous medium and μ $[Pa \cdot s]$ is the dynamic viscosity of the fluid. The negative sign indicates that the flow is in the opposite direction of the pressure gradient. This law can be theoretically derived from the Navier-Stokes equations via homogenization. Here, a permeability parameter replaces the complex geometry of the porous medium, what makes Darcy's law very suitable for a continuum macroscopic modelling.

In order to better represent coal behaviour, we are interested in developing a model at the scale of its constituents, *i.e.* cleats and matrix blocks. The continuum approach is adopted in the coal matrix (section 2.2.1) but we derive a channel flow model directly from Navier-Stokes equations for the cleats (section 2.2.2).

2.2.1. *Matrix*

Methane is mainly stored in the coal matrix as adsorbed gas [GRA 87] but once the pressure is decreased in the cleats, the coal becomes less capable of retaining the methane adsorbed (section 2.1). Gas molecules are firstly desorbed at the coal matrix-cleat interface, what establishes a gas concentration gradient between the cleats and the coal matrix. This concentration gradient is a driving force for methane migration. Since the matrix micropores are small compared with the mean free path[3] of the gas molecules, the transport process is different from Darcy's advection, it is a diffusion process.

Due its simplicity, Fick's law [FIC 55] is the most popular approach to evaluate diffusive flow. It states that the flux is directly proportional to the concentration gradient. Rigorously, the thermodynamically correct driving force for diffusion is the chemical potential gradient. Indeed, diffusion is a spontaneous process reducing the total free energy. As the chemical potential generally increases with increasing concentration, it is convenient to express diffusion in term of concentration or mass density. The flux in the direction i for the species α is then given by :

$$J_{\alpha i} = -D_\alpha \frac{\partial C_\alpha}{\partial x_i} \tag{4}$$

Equation (4) is known as the Fick's first law. It is written in three dimensions, like the diffusion phenomenon actually occurs. In this equation, the determination of the phenomenological coefficient D_α $[m^2/s]$, hiding thermodynamic phenomena, is naturally the most critical part of the equation. Note that when the pores are very narrow, diffusing molecules collide with the walls much more frequently than with other molecules. It results in a sliding of the gas molecules along the internal walls of the porous network, it is the Knudsen diffusion. It does not modify the form of the equation of diffusion.

2.2.2. *Cleats*

In order to develop our channel flow model in a cleat, we first consider saturated conditions. It could be employed at the beginning of the CBM production before a gas flow is established or in the case the coal deposit is not an aquifer and only gas is encountered. Otherwise, unsaturated conditions have to be considered.

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[2] It is written in this form to facilitate the comparison with the channel flow model.
[3] It is the average distance of all the paths followed by a molecule between two collisions.

Saturated conditions

We make the assumption that the cleats are two closely-space parallel plates. Thence, the geometry is given for the cleats and we can directly derive a constitutive law from Navier-Stokes. Assuming laminar flow, steady state conditions and no body force, we can solve easily Navier-Stokes with no-slip boundary conditions. We find the following average velocity over the thickness h between the two plates :

$$q = -\frac{h^2}{12} \cdot \frac{1}{\mu} \frac{\mathrm{d}p}{\mathrm{d}s} \tag{5}$$

We recognize here the Darcy's equation (3) with a permeability equal to $k = \frac{h^2}{12}$ [WIT 80], it is function of the cleat aperture. Note that through the fractured medium, the permeability would be $k = \frac{h^3}{12w}$ where w is the width of the matrix block.

The channel flow model is derived with no-slip boundary conditions. However, it may be not the case for gas flow (single phase). The problem of gas slippage and its effect on permeability in porous media was first addressed by Klinkenberg [KLI 41]. Solving Navier-Stokes equation with the slip boundary conditions proposed by [KUN 75], it can be shown that the permeability should be increased by a factor f_c $[-]$:

$$f_c = \left(1 + \frac{b}{\bar{p}}\right) \tag{6}$$

where $\bar{p}$ is the mean gas pressure in the cleat and b is the Klinkenberg coefficient, it is a function of the mean free path of the gas molecules. Permeability thus depends on factors which influence the mean free path, such as the pressure, temperature, and the nature of the gas.

This channel flow model developed in saturated conditions is straightforward, it allows to directly link the fluid velocity with the cleat apertures which are stress-dependent. So, cleat apertures will be derived from the mechanics and will provide directly the permeability value of the cleats.

Unsaturated conditions

Generally, gas and water flows are simultaneously encountered in the cleats and it is therefore necessary to extend the model to unsaturated conditions. In this purpose, we introduce the widely-used concept of *relative permeability* k_r as a measure of the reduction in permeability to a given phase that occurs between partially and fully saturated conditions. It allows to rewrite the flow equation in the following form :

$$q_i = -\frac{k_r \cdot k_{ij}}{\mu} \frac{\partial p}{\partial x_j} \tag{7}$$

In petroleum engineering, the relative permeabilities of the wetting phase (k_{rw}) and the non-wetting phase (k_{rnw}) in porous media are often expressed as power law functions of saturation (S_w), known as Corey functions [COR 54]. The model was derived on the assumption of a bundle of capillary tubes with various radii in the porous medium [PUR 49]. The same mathematical expressions can be developed considering a flow between parallel plates instead of capillary tubes. Therefore, the relative permeabilities for a fractured reservoir can be expressed as [CHE 13] :

$$k_{rw} = (S_w^*)^{\eta+1+\frac{2}{\lambda}} \tag{8}$$

$$k_{rg} = (1 - S_w^*)^{\eta} \cdot \left[1 - (S_w^*)^{1+\frac{2}{\lambda}}\right] \tag{9}$$

where S_w^* is the normalized wetting phase saturation, η is a tortuosity parameter [MUA 76] and λ is a cleat size distribution index (controlling the difference in the cleat size). The normalized wetting phase saturation is expressed by :

$$S_w^* = \frac{S_w - S_{w,res}}{1 - S_{w,res} - S_{g,res}} \tag{10}$$

with $S_{w,res}$ and $S_{g,res}$ the residual water and gas phases saturations. Equations (8) and (9) are derived from a macroscopic approach and are interesting in this perspective. However, if we want to model the flow at the scale of a single cleat, it is not suitable.

Logically, the space occupied by one phase is not available for the flow of the other phase. Based on the work of Romm, a simple model consists to equalize the relative permeabilities to the phases saturations, it is known as the X curves [ROM 66]. In this case, the sum of k_{rw} and k_{rg} equals 1, which means that each phase flows in its own path without impeding the flow of the other, the interference between the phases is not considered. X model may no longer be valid if the interference is significant.

Assuming a simple flow structure, it is possible to derive a model that takes into account the interference between the two phases through viscous considerations. Yuster used co-axial flows in a single circular cylinder to infer a viscosity ratio dependence of the relative permeabilities [YUS 51]. This viscous coupling model can also be applied to a two-phase flow between two plates with a planar interface between the two fluids [FOU 98]. Water is the wetting fluid and therefore is in contact with the walls, and gas flows in between. Integrating Stokes' equation in each stratum with the assumption that the velocity of each phase is the same at the interface, we finally find the following relative permeabilities :

$$k_{rw} = \frac{S_w^2}{2}(3 - S_w) \qquad (11) \qquad\qquad k_{rg} = (1 - S_w)^3 + \frac{3}{2}\mu_r S_w(1 - S_w)(2 - S_w) \qquad (12)$$

where $\mu_r = \dfrac{\mu_g}{\mu_w}$ is the viscosity ratio. For μ_r equal to one, the sum of the k_r is also equal to one ; however, k_r is not equal to saturation as for the X model. In fact, for gas and water two-phase flows, the viscosity ratio is largely lower than one and the second term on the right-hand side of equation (12) is negligible.

2.3. *Mass balance equations*

We first present the macroscopic approach as usually employed in the literature to simulate coalbed methane production, then the microscopic hydraulic balance equations are presented.

2.3.1. *Macroscopic approach*

Water is assumed only encountered in the cleat system, we have the following single water mass balance equation :

$$\frac{\partial}{\partial t}(\rho_w \phi_f S_w) + \frac{\partial}{\partial x_i}(\rho_w\, q_{w\,i}) = 0 \qquad (13)$$

where ρ_w is the water density and ϕ_f is the cleat porosity (derived from block geometry). The storage term corresponds here to a variation of the water saturation in the cleat void. For the second term, $q_{w\,i}$ is given by equation (7) in which the intrinsic permeability is the homogenized one and the relative permeability is evaluated with equation (8), suitable for the macroscopic approach.

For gas, a dual-porosity approach is adopted [BAR 60]. It consists of using a double continuum with mass transfer between the two systems. This concept, introduced by Barenblatt, requires to define a pressure for both cleats (subscript f) and matrix (subscript m). The governing equations[4] are :

$$\underbrace{\frac{\partial}{\partial t}\left(\rho_{g,f}\ \phi_f(1 - S_w)\right) + \frac{\partial}{\partial x_i}\left(\rho_{g,f}\ q_{g,f\,i}\right)}_{\text{Gas phase}} + \underbrace{\frac{\partial}{\partial t}\left(H\rho_{g,f}\ \phi_f S_w\right) + \frac{\partial}{\partial x_i}\left(H\rho_{g,f}\ q_{w\,i} + S_w\ J_{g\,i}\right)}_{\text{Dissolved gas in water phase}} = m \qquad (14)$$

$$\text{and} \qquad \frac{\partial}{\partial t}\left(\rho_{g,Ad}\right) = -m \qquad (15)$$

Equation (14) is relative to the cleats. In this equation, the first brace is relative to the dry air phase while the second one is to the dissolved gas in water. For the dry gas phase term, the quality $q_{g,f\,i}$ can be evaluated with equation (7) in which the relative permeability is given by equation (9). In the case the cleat is saturated with gas, permeability should be multiplied by f_c from equation (6) to account for slippage on the walls. In the case there is two phases, gas may be dissolved in water. It is thus transported with the water flow and may diffuse in the water following the Fick's law (equation 4). Henry's coefficient H allows determining the dissolved gas volume in the water [COL 02].

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[4] Gas density or concentration may be switched with the gas pressure thanks to the gas equation of state.

Equation (15) indicates the rate of gas "storage" equals the mass transfer with the cleats. This rate is the variation of the amount of gas adsorbed within the matrix, it may be evaluated with the Langmuir isotherm (section 2.1) taking the gas pressure in the matrix.

Finally, the right hand sides of the equations (14) and (15) are the mass exchange term between the matrix and the cleats. It is the difference in pressure between the cleats and the matrix which is responsible for mass transfer m, it is a source for one and a sink for the other. For dual porosity reservoirs, the drainage rate per unit bulk volume from matrix to cleats was idealized by Warren and Root [WAR 63]. Employing a Fickian form, it gives :

$$m = \omega \, D \, M \, (C_m - C_f) \tag{16}$$

with M the gas molar mass and where the parameter ω is a shape factor with the dimension of reciprocal area. It takes into account the geometry of the matrix block in the release of gas. Different authors derived various expressions [WAR 63, KAZ 76, COA 89, ZIM 93, LIM 95]. In fact, the mass transfer between cleat and matrix is approximated for the transient period before the establishment of the pseudo-steady state.

2.3.2. *Microscopic approach*

Contrary to the macroscopic approach, cleats and matrix are represented by separated elements and any transfer function is required.

Matrix

The mass balance equation for gas in the matrix is :

$$\frac{\partial}{\partial t}\left(\rho_{g,Ad}\right) + \frac{\partial}{\partial x_i}\left(J_{g_i}\right) = E_{Matrix \rightarrow Cleats} \tag{17}$$

where the pressure used to evaluate the desorption varies inside the matrix. The second term is related to the gas diffusion, J_{g_i} is given by equation (4).

Cleats

In the cleats, we have both gas and water. The mass balance equations are written for each one.

The mass balance equation for water is :

$$\frac{\partial}{\partial t}(\rho_w S_w) + \frac{\partial}{\partial x_i}\left(\rho_w \, q_{w_i}\right) = 0 \tag{18}$$

Note that, compared with equation (13), any porosity appears since a cleat is entirely a void volume. About q_{w_i}, it is still evaluated with equation (7) but this time the intrinsic permeability is $k = \frac{h^2}{12}$ and the relative permeability is given by equation (11).

Concerning the mass balance equation for gas, we have :

$$\underbrace{\frac{\partial}{\partial t}\left(\rho_{g,f}\,(1 - S_w)\right) + \frac{\partial}{\partial x_i}\left(\rho_{g,f}\; q_{g,f_i}\right)}_{\text{Gas phase}} + \underbrace{\frac{\partial}{\partial t}\left(H\rho_{g,f}\; S_w\right) + \frac{\partial}{\partial x_i}\left(H\rho_{g,f}\; q_{w_i} + S_w \; J_{g_i}\right)}_{\text{Dissolved gas in water phase}} = E_{Cleats \rightarrow Matrix} \tag{19}$$

The flow q_{g,f_i} is evaluated with equation (7) in which the relative permeability is given by equation (12).

3. Conclusion

As changes in reservoir properties are a crucial issue for the coalbed methane recovery, ignore the geomechanical processes inevitably leads to errors in the assessment of reserves. Suitable tools are therefore required. Classical macroscopic modelling approaches are inadequate for dual porosity systems. Indeed, these approaches use a single continuum discretization and the behaviours of the matrix and the cleats are therefore homogenized, what improperly simplifies sorption- and stress-induced coal permeability alteration.

Instead of a single continuum, we presented a macroscopic approach with a double continuum to model the hydraulic behaviour of coal. This approach takes into account the dual behaviour of coal through a mass transfer term depending on a shape factor. However, the choice of the shape factor is not unique in the literature and moreover, the actual factor may be not constant. To overcome the need of a shape factor, we can explicitly model the gas diffusion in the matrix and the transfer between the matrix and the cleats. With a microscopic approach, cleats and matrix are represented by separated elements and the transfer occurs through the boundaries of the different elements. This approach best represents the hydro-mechanical couplings since the discretization is made at the scale of the constituents. However, direct modelling of the full microstructure is usually not possible due to the high computational expense it would require at the scale of a reservoir. Thence, the microscopic approach presented in this article has to serve as basis for a multi-scale approach. The idea would be to model the micromechanical effects explicitly on their specific length scale and couple their homogenized effects to the macroscale.

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