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Laboratory-Scale Study On The Swelling Behaviour Of Coal Due To CO2 Injection

F. Bertrand[1,2]*, O. Buzzi[2], F. Collin[1]
[1]University of Liege, [2]University of Newcastle

Summary

Sorption- and stress-induced coal permeability alteration may occur considering injection of carbon dioxide in coal seams for CCS. To take into account properly these phenomena, a microscale model was developed for the modelling of injection experiments carried out in laboratory. This work presents this model and first experimental results obtained from an injection test.

Introduction

Carbon Capture and Storage (CCS) technologies could help mitigating anthropogenically-driven climate change by reducing the lifecycle greenhouse gas emissions of fossil fuel power plants [1]. In particular, the sequestration into un-mined coal seams may be an economical option for CCS [2]. Indeed, coal seams are known to generally contain large amounts of methane that can be recovered in the form of natural gas. As carbon dioxide has a stronger affinity for coal than methane, it can displace the methane molecules to enhance the production while the carbon dioxide is trapped. However, the complex chemo-mechanical interaction between coal and carbon dioxide involving, for example, coal swelling needs to be understood and predicted [3,4].

Modelling such coupled phenomena requires more complex models than those normally used for conventional reservoirs. For instance, a reservoir-scale model accounting for sorption- and stress-induced coal permeability alteration is presented in [5]. This paper presents a laboratory-scale multiphysics model.

Laboratory-scale model description

Coal is a porous and fractured medium [6] and, to deal with the permeability evolution with stresses and volume of adsorbed CO_2, the model has to take into account the distinct behaviour of the fractures, called cleats, and the matrix. At the laboratory-scale, cleats can be explicitly modelled with interface elements [7]. *Figure 1* presents a basic geometry made of matrix blocks delimited by zero-thickness elements. If gas is injected, for instance at the bottom of the sample, it is first adsorbed close to the fractures since it is generally a preferential pathway for the fluid.

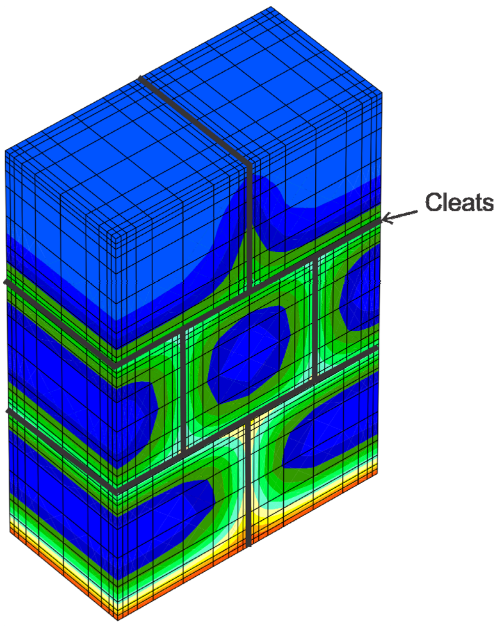

Figure 1 *Adsorbed gas pressure during an injection test performed with a basic geometry.*

The cleats permeability is estimated by assuming that the fluid flows in between parallel and smooth plates and by comparing Darcy's equation with the mean velocity obtained by solving Navier-Stokes' equations. The cleats permeability was found to be proportional to the square of the hydraulic aperture [8]. Then, from the boundary of the matrix imposed by the cleats, gas diffuses in the matrix following Fick's law [9].

The cleat aperture h, used to compute the permeability, is affected by the stress state in the material:

$$\dot{h}_{(x)} = \frac{\dot{\sigma}'_{(xx)}}{K_{n_{(x)}}}$$

where K_n is the normal stiffness of the fracture and σ' is the effective normal stress. A hyperbolic law is used to describe the evolution of the stiffness with the fracture aperture [10]. The stress state may be affected by the sorption or desorption from the matrix. Indeed, sorption-induced strain can be compared to thermal dilatation: if the material is constraint by the boundary conditions, internal stresses are induced in the material and the permeability may be altered. The volumetric sorption-induced strain ε_{vs} is assumed isotropic and is theoretically related to the volume of adsorbed gas $V_{g,Ad}$ [11]:

$$\varepsilon_{vs} = \beta_\varepsilon \cdot V_{g,Ad}$$

where β_ε is a linear coefficient, called the swelling strain coefficient. The gas content in the matrix $V_{g,Ad}$ depends on the gas pressure in the cleats. For a given temperature, the Langmuir's isotherm represents the maximum quantity of gas that can be stored in the matrix [12].

The coal matrix follows a linear isotropic elastic constitutive law but the assembly of coal blocks (matrix separated by cleats) displays a non-linear anisotropic behaviour.

This model is implemented in the Finite Element code Lagamine [13].

Model calibration

In addition to the geometry of the sample, a dozen of parameters are used to describe the mechanical and hydraulic behaviours of the cleats and the matrix. One of the most important parameters is the swelling strain coefficient β_ε. In order to determine this parameter, a swelling experiment was set up. Four gas pressure values were applied to a dried cubic specimen of coal (size of approximately 5cm) and the volume change was recorded for each pressure increment. *Figure 2 (a)* presents the evolution of volumetric strain with time. The final strain for each step is reported in the second graph and compared to the numerical simulation. These results were used to infer the swelling strain coefficient.

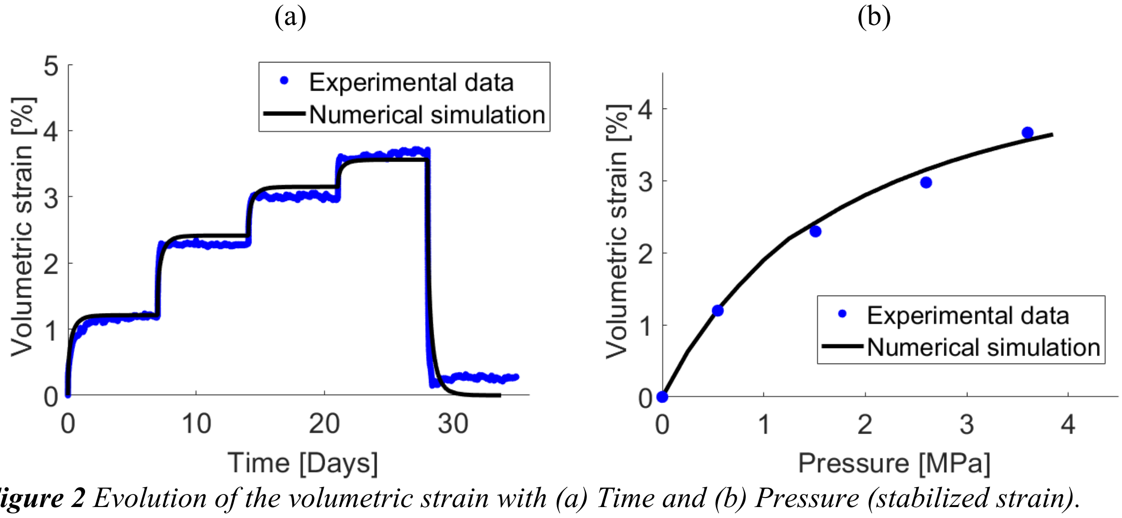

Figure 2 *Evolution of the volumetric strain with (a) Time and (b) Pressure (stabilized strain).*

Preliminary Results

The model can model the evolution of permeability during a CO_2 injection test. The geometry shown in *Figure 1* was used for the numerical simulations. Figure 3 presents the boundary conditions which are employed. These boundary conditions are such that the sample is not free to swell (all displacements constrained). Preventing the volumetric strain results in a closure of the internal cleats and a decrease of the permeability.

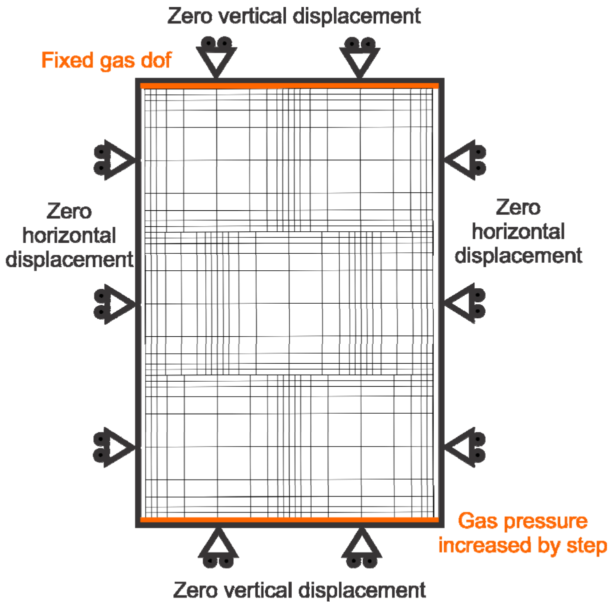

Figure 3 *Boundary conditions used to simulate the injection test.*

Figure 4 (a) represents the evolution of the normalised cleat permeability (it is the cleat permeability divided by the initial one) with dimensionless time (it is normalised by the diffusion coefficient and the height of the sample) for different pressure increments. The permeability at the end of each step is reported in the second graph to highlight the evolution of the permeability with the injection pressure. The dotted line is the minimum permeability that can be achieved given the material parameters that are used.

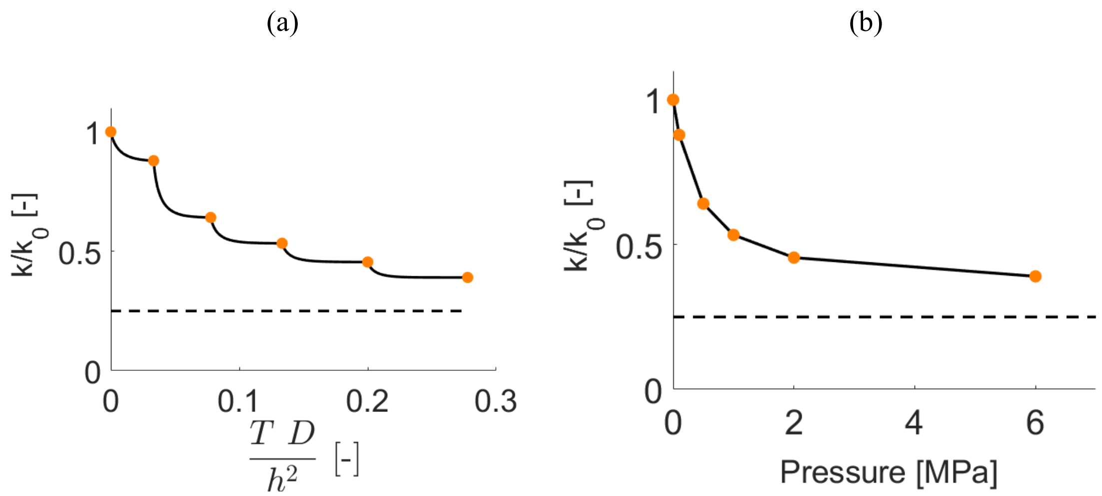

Figure 4 *Evolution of the normalized cleat permeability with*
(a) Dimensionless time (T=Time, D=Diffusion coefficient, h=Sample height) and
(b) Pressure (stabilized permeability).

Conclusions

A model has been developed at the scale of the coal constituents for the modelling of laboratory experiments such as gas injection tests. Given the swelling properties of the material measured in laboratory, the simulation of an injection test shows that the permeability decreases with the increase of CO_2 pressure. Although the simulation was performed with fixed boundary conditions, in order to highlight the effect of cleat closure, such boundary condition is not trivial to achieve in the laboratory and constant confinement pressure is more likely to be used. For such boundary conditions, the specimen is not free to swell but the deformations are not totally prevented. The permeability evolution therefore depends on the confinement pressure and injection pressure applied. This coupling can be captured by the model.

In the perspective of reservoir modelling, the model is also implemented for unsaturated conditions. The permeability functions of the two fluids are inferred from considering that flow occurs within planar interfaces and integrating Stokes' equation in each stratum. These expressions depend on the saturation degree, what requires the definition of a retention curve in a single fracture. Moreover, direct modelling of the microstructure is not possible for the entire reservoir due to the high computational expense it would require. However, the laboratory-scale model can be integrated into a multi-scale approach. These aspects have not been detailed here as the modelling was restricted to gas saturated conditions at the laboratory-scale.

Acknowledgements

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