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Experimental study of the gas permeability and bulk modulus of tight sandstone and changes in its pore structure

Yi Wang[a,b,*], Franck Agostini[a,b], Frédéric Skoczylas[a,b], Laurent Jeannin[c], Éric Portier[c]

[a] School of Civil Engineering and Architecture, Hubei University of Technology, Wuhan, China
[b] Laboratoire de Mécanique de Lille (LML) FRE CNRS 3723 and Centrale Lille, Villeneuve D'Ascq Cedex, France
[c] ENGIE E & P International, La Défense Cedex, France

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ABSTRACT

Tight sandstones samples from an Ordovician gas field in Algeria studied in this work are characterized by low connected porosity (below 10%) and low gas permeability (below 0.1 mD under ambient condition). Under confining pressure (up to 40 MPa) the permeability has decreased by more than 80% while the porosity goes down between 10% and 25%. Regarding the porous structure which is constituted of large angular pores connected by micro-cracks, the high stress-sensitivity of permeability is mainly the result of micro-crack closure. In addition, the decrease of porosity potentially involves porosity trapping up to a confining pressure of 20 MPa caused by the closure of certain cracks. This hypothesis is further supported by the pore volume variation test and poro-mechanical test. The resulting improvement in our understanding of these physical phenomena will be very useful in the forthcoming analysis of the combined impact of water saturation and confinement on the effective gas permeability of this type of sandstone.

1. Introduction

When compared to "conventional" sandstones, so-called "tight" sandstones are characterized by low connected porosity (less than 10%), low gas permeability (less than the mD, i.e. of the order of 10^{-16} m^2), and very high sensitivity to confining pressure.[1–5] A gas reservoir in this kind of low permeable rock is referred to as an "unconventional tight gas reservoir". A study of the economic efficiency associated with the potential extraction of gas from such a reservoir unavoidably relies on a full understanding of its permeability, its porosity, and the variation of these characteristics as a function of pressure and water saturation.

The economic challenge of such reservoirs has led to considerable research on the tight sandstones. These studies have focused on the influence of pressure conditions on their permeability and porosity. Many authors have emphasised the fact that the permeability can be significantly modified at low confining pressures,[5–12] even though this low level of pressure has only a limited influence on its porosity.[11,13] The influence of pressure is thus more strongly related to the rock's porous structure and morphology than to a simple decrease in porous volume induced by confining pressure. Previous research[3,5,6,9,14] shows that the porous structure of tight sandstone is often made up from pores that are interconnected by the presence of a network of micro-cracks or joints around quartz grains. It is thus very likely that the flow of gas is more strongly dominated by the opening and closing of these micro-cracks, than by the reduced size of their pores. Numerical models have often been developed on a more or less empirical basis, in an attempt to characterise the relationship between permeability and porosity, and are often based on the use of power laws.[10,13,15,16] The general applicability of such relationships, which implicitly require all types of pore to have a similar influence on the flow of gas, should however be questioned. Some models (for example TPHM[13,17] try to distinguish between the contrasted influence on permeability of the "angular" pores, and that of micro-cracks, and their relationship to changes in porosity). However, as they do not take interactions between these two families of pores into account, the scope of these models is limited. In practice, it would make sense to expect the gas flow to be dominated by micro-cracks, with their closure leading to the isolation of large pores, which are then trapped inside the matrix.[3,18,19] These pores could then be associated with a direct "loss" in connected porosity.

For this experimental study, ten samples from a tight sandstone reservoir in North Africa[20] have been tested in term of porosity and permeability variations as a function of confining pressure. Detailed analysis of these variations in these properties highlights the importance of the micro-crack network in terms of gas flow, and shows that,

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[*] Corresponding author at: Laboratoire de Mécanique de Lille (LML) FRE CNRS 3723, and Centrale Lille, CS20048, F-59651 Villeneuve D'AscqD'Ascq Cedex, France.
E-mail address: yi.wang@ec-lille.fr (Y. Wang).

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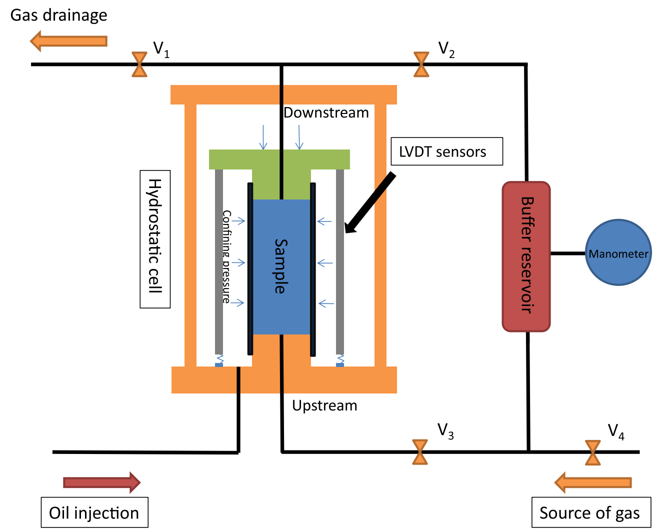

Fig. 1. Device for the measurement of a sample's gas permeability, gas porosity and poro-mechanical properties.

above a certain level of confining pressure, a high proportion of the rock's porosity is trapped inside the solid matrix. This phenomenon is analysed in poro-mechanical terms, thus confirming, independently of any transfer considerations, that trapped porosity has a significant impact on the poro-mechanical properties of the studied sandstone.

2. Experimental tools and measured properties

2.1. Gas permeability

Although the gas permeability of tight sandstone is considered to be low in comparison with that of conventional sandstone, it is nevertheless sufficiently high to be measured with quasi-stationary flow techniques.[21,22] A sample is placed in a hydrostatic cell, and is isolated from the confining pressure oil by means of an EPDM membrane. The confining pressure is applied by increasing the oil pressure, and the gas permeability is measured by a well-proven technique, which is described in detail in 22. A drawing of the test apparatus is shown in Fig. 1.

2.2. Gas-accessible porosity

The gas porosity test[23] is found to be a highly useful tool for the study of variations in a material's porous structure. This test can also be carried out in a confinement (or triaxial) cell, thus allowing variations in connected porosity to be monitored, as a function of loading. In the case of tight sandstones, this information is invaluable when it is correlated with the material's characteristic "hydraulic cut-off" behaviour. This is a kind of "reverse" pycnometer test. The sample having a certain pore volume V_{pore} is placed in the cell, and is connected to a set of pipes and drainage baseplates with a measured and calibrated internal volume V_t (Fig. 1). The experimental set-up is connected to a buffer volume, which is a reservoir having a very well calibrated volume V_b. The test is carried out under isothermal conditions, and over a range of gas pressures allowing the ideal gas law to be used:

$$PV = nRT \tag{1}$$

The reservoir is loaded with an initial pressure P_{ini}. A system of valves is then opened, connecting it to the sample via the internal volume V_t. The pressure settles to a final value P_f, leading to:

$$P_{ini} V_b = nRT = P_f (V_b + V_t + V_{pore}) \tag{2}$$

This simple calculation gives the value of V_{pore}, and thus the gas porosity:

$$\phi_g = V_{pore}/V_{sample} \tag{3}$$

The volume of the sample V_{sample} is measured with a calliper gauge or by means of hydrostatic weighing.

2.3. Measurement of the material's poro-mechanical properties

The poro-mechanical measurements presented in this study have been well described by Biot,[24] Zimmerman[25] and Coussy.[26] These experiments were again designed to study the effects of confining pressure on a material's porous structure, and as a complementary measurement to that of the material's gas porosity under loading. From a practical point of view, the closure of cracks or joints under loading can disconnect some pores that become inaccessible to the ambient gas. When describing the porous medium, the "changeable" status of these pores means that they may, or may not, belong to the material's solid matrix, and can thus have an influence on its rigidity (K_s). The closing of cracks will influence the rigidity (K_b) of the skeleton. Poro-mechanical measurements are made in this context only. As a consequence, only the volumetric deformation ε_v is measured in the material, considered to be isotropic. This deformation is acquired through the use of four LVDT sensors, which are diagonally opposite (Fig. 1). Each LVDT allows an axial deformation ε_i to be computed, from which the volumetric deformation is given by:

$$\varepsilon_v = \frac{3}{4}(\varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4) \tag{4}$$

Biot's theory can be applied in cases where the material is elastic. In the presence of cracking, its properties are thus measured at different levels of confining pressure, through the use of small decrease in confining pressure (ΔP_c), or increase in pore pressure (ΔP_i). In particular, the term K_b is a modulus given by (unloading step):

$$K_b = \frac{\Delta P_c}{\Delta \varepsilon_v^c} \tag{5}$$

The matrix modulus K_s can be measured indirectly via the modulus H, providing the volumetric deformation as a function of an increase in pore pressure ΔP_i. This leads to:

$$H = \frac{\Delta P_i}{\Delta \varepsilon_v^i} \tag{6}$$

Finally, Biot's coefficient is given by the ratio $b = K_b/ H^{25}$. We note that in both cases of confining pressure, unloading or pore pressure loading, an elastic phase is experienced (unloading under effective pressure).

During confining pressure (re)loading (ΔP_c), it is possible to apply gas pressure loading ΔP_i in order to obtain $\Delta \varepsilon_v$, which according to Coussy [26] will lead directly to K_s, since K_s=(ΔP_c= ΔP_i)/$\Delta \varepsilon_v$.

It can be noted that with all of these experiments, the properties of interest are determined with the help of a gas (argon) used as interstitial fluid. This technique is frequently used in the laboratory, and makes it possible to remain close to *in-situ* conditions (poro-mechanical coupling arises from gas pressure), and to test the materials under conditions of partial water saturation, whenever necessary.

3. Results and discussion

3.1. Material, initial characterization

The samples were taken from a field located in North Africa,[20] at depths between 2000 and 2500 m. They were prepared by ENGIE EPI in the form of 37 mm diameter, 60 mm long cylinders. Their values of water porosity (assessed by water imbibition) and initial gas permeability at 3 MPa of confining pressure were measured, and are provided in Table 1 below. Depending on the sample, the measured values of water porosity vary between 1.5% and 5.0%, which is low for