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Gas recovery potential of sandstones from tight gas reservoirs

Z. Duan [a,b,c], C.A. Davy [a,b,c,*], F. Agostini [a,b,c], L. Jeannin [d], D. Troadec [e], F. Skoczylas [a,b,c]

[a] Université Lille Nord de France, F-59000 Lille, France
[b] LML, CNRS, UMR 8170, F-59650 Villeneuve d'Ascq, France
[c] Ecole Centrale de Lille, CS20048, F-59651 Villeneuve d'Ascq cedex, France
[d] GDF/Suez E&P International SA, 1 place Samuel de Champlain, 92930 Paris La Défense cedex, France
[e] IEMN, UMR CNRS 8520, Avenue Poincaré, BP60069, 59652 Villeneuve d'Ascq Cedex, France

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ABSTRACT

The aim of our experimental study is to characterize experimentally the petro-physical properties of a set of sandstones originating from different depths from a single tight gas field, in order to improve our knowledge on their gas recovery potential. The initial characterization of these sandstones is performed in the dry state, and in the "as received" states: porosity, initial water saturation level, and gas permeability at a confining pressure of 5 MPa. For two different samples under increasing confining pressure, we have evaluated the water saturation threshold, above which no more gas passes through the porous network, owing to hydraulic cut-off, to be about 63–68%. Then, at intermediate saturation level (on the order of 40%), two different sample types were identified, depending on whether their relative gas permeability is affected, or not, by confining pressure. For one sample of each type, poro-elastic experiments show that the variation in normalized matrix bulk modulus (due to confining pressure increase) may be attributed to the closure of portions of the connected pore network. Finally, to ascertain the above, a dedicated test was designed to measure the pore volume changes under confinement, simultaneously to volumetric strains. Whenever pore volume variation is significantly higher than volumetric strains, pore trapping is identified; otherwise, microstructure changes are mainly attributed to crack closure.

1. Introduction

So-called *tight gas reservoirs* are constituted of low permeability sandstones, whose petro-physical properties may hinder proper gas recovery [1]. They have a low absolute permeability (below 0.1 mD i.e. 10^{-16} m^2 under ambient conditions), a connected porosity lower than 10%, and a strong sensitivity to *in situ* stresses compared to conventional reservoirs [2–8]. Moreover, a large transition zone related to capillary pressure effects is observed *in situ*. This zone, where partial water saturation is greater than irreducible water saturation, may extend over several hundreds of metres above the free water table. Inside this zone, the effective gas permeability is strongly reduced compared to absolute gas permeability and neither gas nor water may be sufficiently mobile for industrial extraction; it is the permeability jail [9], which is also called hydraulic cut-off.

Our contribution is focused on sandstones cored at different depths from a single well of a tight gas field in Algeria [10]. Our aim is to determine whether they are prone to the permeability jail. First, we characterize the initial petro-physical properties of the different available sandstones: these are mainly their initial water saturation level, water porosity, and dry and relative gas permeability at low confinement [11]. The initial microstructure is assessed by Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS) analysis and FIB/SEM (Focused Ion Beam/SEM) imaging [14,15].

Second, at low confining pressure (on the order of 5 MPa), an experimental study is performed, in order to identify the actual water saturation level corresponding to the permeability jail, i.e. when gas no longer *significantly* crosses the pore network.

Further, we investigate the gas transport sensitivity of these sandstones to confining pressure (P_c) changes at an intermediate water saturation level (35–46%), by measuring the evolution of gas relative permeability with P_c. This sensitivity to external stress is interpreted as being due to changes in sandstone microstructure, i.e. either micro-crack closure or pore trapping. It is also investigated by using poro-mechanical experiments [12,13]. These provide insights into the relationship between external confining stress and (1) drained bulk modulus K_b and (2) normalized solid matrix bulk modulus K_s.

Finally, a dedicated test, which is similar to a gas pycnometric experiment [19], is performed to measure directly the change in

* Corresponding author.
E-mail address: catherine.davy@ec-lille.fr (C.A. Davy).

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Table 1
Sample number with their type of pore microstructure, initial water saturation level S_w, porosity ϕ_w (measured by the water saturation method) and initial (not fully dry) gas permeability K_{gas} at confinement $P_c = 5.6 \pm 0.3$ MPa.

Sample no.	Pore microstructure type	S_w (%)	ϕ_w (%)	K_{gas} (10^{-17} m^2)	P_c (MPa)
2390-82	Type 1 (mainly narrow joints)	19.8	3.2	3.74	5.9
2391-82	Type 1	23.3	1.8	1.32	–
2377-75	Type 3	19.1	6.9	7.6	5.8
2386-59	Type 2 (clay or precipitated minerals filling around quartz grains)	10.7	4.1	Not assessed	–
2378-83	N/A	15.5	6.5	15.7	5.4
2383-52	Type 3 (rounded pores and narrow joints)	14.3	6.8	2.4	5.3
2375-15	Type 1	18.2	5.1	4.3	5.8
2384-53-1	Type 2	23.2	7.7	28.4	5.3
2379-18	N/A	0.4	6.7	5.11	5.4
2376-97	N/A	17.9	6.8	4.7	-
2399-87	N/A	4.8	4.0	40	5

pore volume simultaneously to volumetric strains, in order to assess our interpretation of microstructure changes, i.e. as being due to actual pore trapping or solely to micro-crack closure.

2. Experimental methods

2.1. Sample preparation

In the following, for the assessment of gas transport and poro-mechanical properties, we test up to 11 samples cored at different depths in the same well, see Table 1. They are supplied to our laboratory in the shape of cylinders, with a diameter of 38.13 ± 0.02 mm and a height ranging between 31.41 and 37.22 mm (with an average value of 36 mm).

Water porosity ϕ_w is defined as $\phi_w = (m_{saturated} - m_{dry})/(\rho_{water} V)$, where $m_{saturated}$ and m_{dry} are the saturated and dry masses, ρ_{water} is the water density and V is the sample total volume. $m_{saturated}$ is measured by immersing the samples under water, inside a vacuumed hermetic chamber until mass stabilization; m_{dry} is obtained by oven-drying at 60 °C (also until mass stabilization). Partial water saturation S_w is defined as $(m - m_{dry})/(m_{saturated} - m_{dry})$, where m is the sample mass at stabilization. S_w is obtained for low values (below 25%) by placing each sample in a relative humidity (RH)-controlled atmosphere until mass stabilization. For values higher than 25%, a specific iterative method has been devised, as follows.

First, as for porosity measurement, the sample is fully water-saturated by water immersion inside a hermetic chamber, where air vacuuming is imposed for several days, until mass stabilization. Regularly (ca. once a day), the sample is surface-dried and weighed at least twice for repeatability. At mass stabilization, it is oven-dried at 60 °C for a few minutes in order to release a very small amount of water, and weighed again, until the desired saturation level is obtained, evaluated from the actual sample mass m (see definition of S_w above). Once the desired S_w is obtained, the sample is wrapped in superposed aluminium and plastic sheets, and allowed to equilibrate for 24 h at least. This aims at helping a proper water redistribution throughout the sample. After 24 h, the sample is unwrapped, placed in a hydrostatic cell (see [13] and Section 2.2) and tested for gas permeability at various confining stress values, from 5 to 40 MPa. After gas permeability testing, the sample is weighed and its saturation level is assessed again. Indeed, due to dry 99%-pure argon gas flow through the sample during permeability measurements, interstitial water gets partially evacuated from the sample. Therefore, results are provided with a given S_w and its variation interval, which corresponds to the variation of S_w before and after test. Further work will tackle saturation levels higher than 60–70%, which require experiments on longer durations.

2.2. Initial microstructure assessment

For SEM and EDS analyses, 36 mm diameter and 5–10 mm-long sandstone samples are oven-dried at 60 °C (until mass stabilization) and impregnated in low viscosity resin (Epofix, Struers™). After polishing and ultrasound cleaning in an ethanol bath, the surface of each sample is coated with a thin gold deposit (EMSCOPE SC500TM metallization instrument, by Elexience™, France). The SEM instrument (HITACHI S3600N™) is used with its secondary electron (SE) detector, or its Back Scattered Electron (BSE) detector. Thanks to proper surface flatness, SEM analysis is coupled to Energy Dispersive X-ray Spectroscopy (EDS) analysis (Thermo Ultra Dry™ detector) for quantitative chemical element determination. The EDS sensor is used with at least 1000 counts per image, at a constant acceleration voltage of 15 kV, and at a nominal working distance of 15 ± 0.2 mm.

FIB (Focused Ion Beam)/SEM provides sequential 2D images of the microstructure, without any preliminary preparation (and damage) of the observed surface, to resolutions lower than those available with our SEM (one pixel represents 15 nm). The sandstone sample surface is finely polished (down to mirror-like polish) and coated with platinum for proper electrical conduction. The focused ion beam (FIB) cuts a U-shaped hole in order to isolate a plane-parallel sandstone volume [14,15]. Following this, the FIB cuts regularly spaced 50 nm thick slices from the plane-parallel volume, perpendicular to the sample polished surface. Between each FIB cutting, the sandstone matter perpendicular to the polished surface is observed with an electron detector of the in lens type, which detects both secondary and backscattered electrons. This provides images reflecting both the sample roughness (thanks to the SE) and its chemical composition (the image contrast is given by the BSE).

2.3. Gas permeability assessment

All permeability tests are performed in a hydrostatic cell, in order to subject the sample to a constant confining pressure (i.e. hydrostatic stress) P_c on its outer surface. Due to expected low values (between 10^{-17} m^2 and 10^{-21} m^2), gas permeability is assessed by the transient pulse test technique [11,16,17,18]. First, the sandstone specimen is subjected to a constant interstitial pore pressure value (static pressure p), and then, it is subjected to a gas pressure increase on its upstream side. The analysis of the pressure difference between upstream and downstream sample sides provides permeability values K_{gas} as low as 10^{-21} m^2, at each