INFLUENCE OF PORE PRESSURE DECLINE ON THE PERMEABILITY OF NORTH SEA SANDSTONES

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ABSTRACT
Absolute permeability and poro-mechanical properties are measured for North Sea sandstones under uniaxial compaction. Loading is done by decreasing pore pressure, and radial stresses are adjusted to keep zero lateral strain. This stress path is representative of reservoir in-situ conditions. A number of laboratory tests simulating real depletion are carried out. Two rock-types (F1, F3) are tested and absolute permeabilities are determined for each sample at different pressure values.

Experimental results are analyzed for each sample. They show that permeability reduction, when pore pressure decreases from 110 MPa to 10 MPa, is about 15% for F1 samples and more than 50% for F3 samples. Then, experimental results are used to derive an empirical law relating permeability reduction to porosity decrease. Taking in account all measurement points, the plot of permeability change as a function of porosity reduction (deformation) shows a substantial correlation when F1 rock-type is considered. In contrast, correlation between permeability change and porosity reduction is not that easy when F3 rock-type is considered.

INTRODUCTION
During petroleum reservoir depletion, pore pressure declines and effective stresses increase, this supplementary loading induces a compaction of reservoir rock and, consequently, permeability reduction. Sometimes, this reduction can reach a level cut. So, it’s of interest to quantify correctly permeability reduction so as to allow for efficient the managing of petroleum reservoir. The first objective of this work is to quantify, using laboratory tests, the effect of pressure decline on reservoir rock permeability.

In the beginning of this project, a new experimental device (COMPLIS system) has been designed. This apparatus is able to measure simultaneously various properties of rocks. It can be used to measure permeability decrease, porosity reduction (pore volume change), Young modulus, Poisson ratio, Biot’s coefficient and electric resistivity in conditions simulating real depletion. Stresses and pore pressure can reach 150 MPa during tests.

In the bibliography, many works dealing with permeability change during reservoir deformation were presented. In the majority of works, laboratory experiments were done with isotropic loading or uniaxial loading without pore pressure, which not simulate real depletion. Models presented, like Cozeny-Carmann relation and Power model, were not validated. Only some works were distinguished by a loading path simulating real depletion. In the last case, experimental results were used to derive empirical models. We can quote as examples the works of GRAY and al (1992), TEUFEL and al (1992).

A number of lab tests simulating real depletion are done. Deformation dependant permeability is investigated under unixial compaction mode (zero lateral strain). Two rock types (F1, F3) are tested. The test program is carried out with sandstone sampled from a North Sea HP/HT reservoir. Samples porosities taken from F1 rock-type varies from 16 % to 27 %, while porosities of F3 rock-type samples are between 16 % and 30 %.
The petrographic composition of HP/HT sandstone can be described as follows: Quartz (~ 70 %), Feldspath (~ 10 %), Mica (~ 2 %), Clay (5 %) and others (Pyrite, Dolomite, Silica).
Absolute permeability, pore volume change (porosity) and deformation are measured step by step from 110 MPa pore pressure to 10 MPa. For the majority of samples, eight measurement points are done; 110 MPa, 95 MPa, 80 MPa, 65 MPa, 50 MPa, 35 MPa, 20 MPa and 10 MPa.

The permeability decrease, when pore pressure goes from 110 MPa to 15 MPa is less than 15 % for F1 facies, and more than 50% for F3 facies. Experimental results are used to derive an empirical law which links permeability decrease to porosity diminution (or deformation). This model developed From "Power" law gives a very good fit and can be used to predict permeability reduction.
In this paper, we describe the experimental device and we develop an empirical equation to describe permeability reduction during reservoir depletion.

EXPERIMENTAL DEVICE

Because the importance of experimental results for this study, a new experimental device called COMPLYS system (fig.1), was designed. This apparatus includes a servo–control unit, triaxial cell and two hydraulic pumps used to apply axial and radial stresses.
Two other hydraulic pumps are used to apply pore pressure and they allowed liquid (brine) to flow through the sample during permeability measurement. Another pump is used to quantify pore volume change when effective stress increases during the test. This device is able to measure simultaneously poro-mechanical properties and permeability of each sample. The maximum of pore pressure and stresses values can reach 150 MPa.

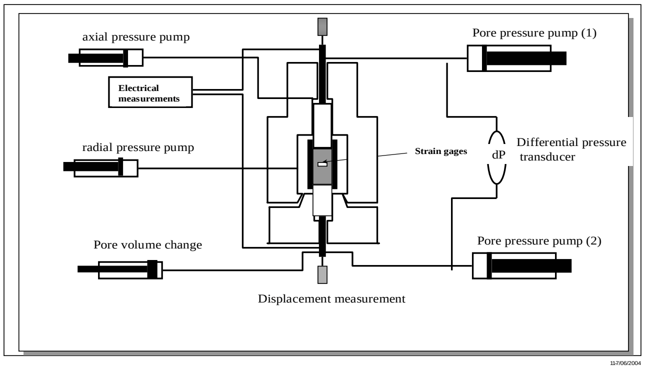

Figure 1. Measurement device

PROCEDURE

The test samples are cores of North Sea sandstone (high pressure – high temperature reservoir). Each sample is cleaned and dried, then, porosity and permeability are measured at confining pressure equal to 2 MPa (routine measurements). Porosity values vary from 15% to 30% and permeability values are between 3 mdarcy and 700 mDarcy. All measurements presented in this paper are run with 4 cm diameter core plugs. Each sample is equipped with two radial strain gages and two axial strain gages then protected with viton – jacket.

In the beginning of test, axial stress, radial stress and pore pressure are increased step by step from, respectively 27 MPa, 17 MPa and 10 MPa until 127 MPa, 117 MPa, and 110MPa. These values are equal to stresses which exist in the reservoir before the beginning of depletion. Thereafter a period of stabilization is imposed. After 24 h, Deformations are stabilized and depletion begins. During the test, axial stress is taken constant, pore pressure is dropped step by step (0,1MPa/mn) and radial stress is adjusted to achieve zero lateral stain. All tests are performed with fluid flow parallel to the specimen axis. Tests are performed with samples having their axes both parallel and perpendicular to the bedding plane. During tests several flow rates are applied to each sample and the line pressure is dropped from 110 MPa to 10 MPa (simulating real depletion).
Axial strain, deformation (LVDT transducer), electrical resistivity, pore volume change and absolute permeability are measured under uniaxial compaction mode at temperature equal to 21°C.

Absolute permeability is determined by measuring the differential pressure between the pore fluid inlet and outlet. A new differential pressure transducer is used to measure differential pressure at very high pore pressure (until 150 MPa).
In the present work, we are interested only by stress-dependent permeability. The other results are not presented in this paper.

RESULTS

Absolute permeability is determined for each sample at different pore pressure values.

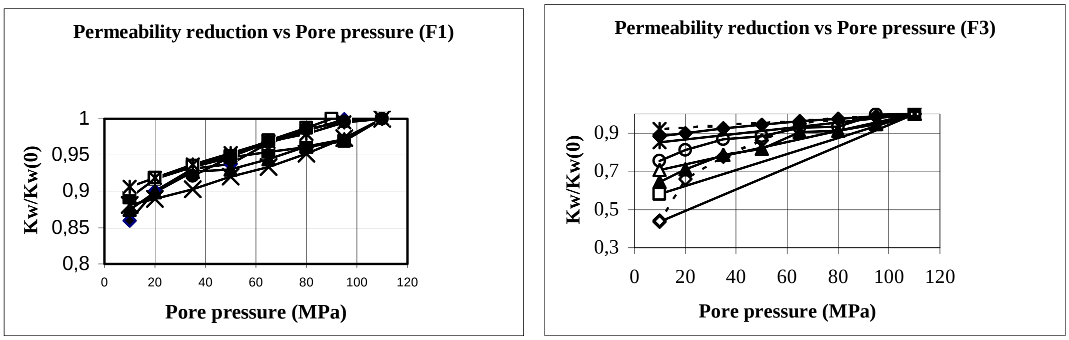

Figure 2 Permeability reduction vs Pore pressure (F1, F3)

Fig 2 shows absolute permeability reduction vs pore pressure decline. The maximum permeability reduction is about 15% for F1 type –rock. It can be observed that permeability reduction is small despite the substantial decrease of pore pressure. This can be explained by the great value of Young modulus for F1 type – rock (more that 15000 MPa) and so a great resistance to deformation. Unlike the F1 type–rock, permeability reduction for F3 type – rock is not negligible and must be taken in account when we simulate production planning.

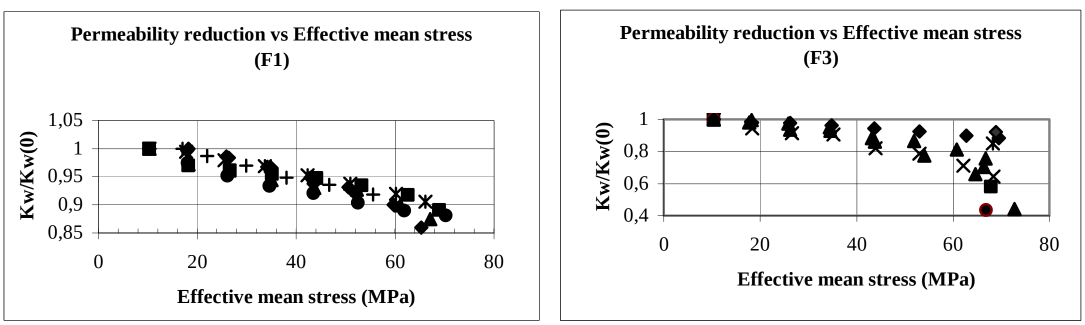

Figure 3 Permeability reduction vs effective mean stress (F1, F3)

Fig 3 shows absolute permeability reduction as a function of effective mean stress. The shape of curves is non-linear. When effective mean stress reach 55 MPa, we can observe that the rate of permeability reduction became more important for F3 than for F1. Permeability change is slightly larger for high effective mean stress.

Relationship between permeability change and porosity reduction (deformation)

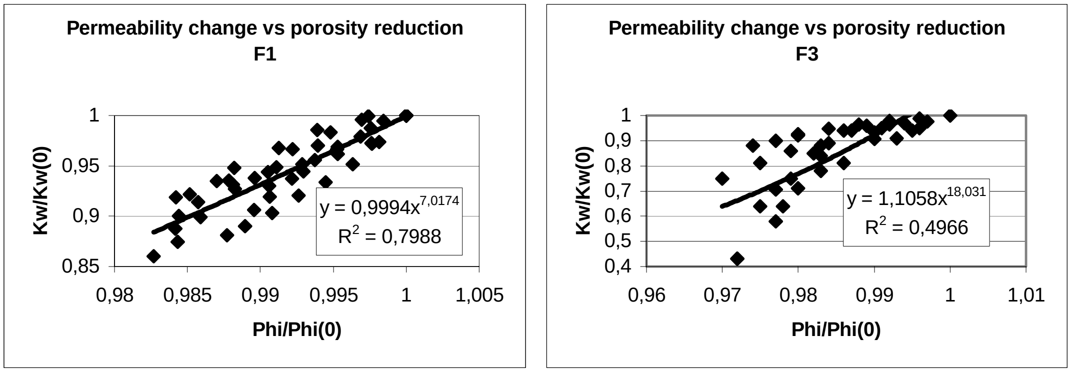

Fig. 4 permeability reduction vs porosity change (F1, F3)

The shape of curves presented in Fig 4 shows that a substantial correlation exists between permeability reduction and porosity change when F1 rock-type is considered. A reasonably good power relationship between permeability change and porosity reduction is easy found (correlation coefficient = 0.8). This relation can be explained by the follow equation:

$$\frac{K}{K_0} = [\frac{\phi}{\phi_0}]^7 \quad (1)$$

In contrast, correlation between permeability change and porosity reduction is not that easy when F3 rock-type is considered.
We can approximate a relationship between permeability change and porosity reduction by the following equation:

$$\frac{K}{K_0} = [\frac{\phi}{\phi_0}]^{18} \quad (2)$$

With:
K= absolute permeability
K_0 = initial absolute permeability (at 110 MPa)
Ø = porosity
$Ø_0$ = initial porosity (at 110 MPa)

Although both rock-types are cored in the same reservoir, previous laws are remarkably different. Hence, this example shows that no general law relating permeability change to deformation exists. Thus, identification of permeability behaviour when pore pressure declines, needs necessary a number of laboratory tests.

CONCLUSION

The experimental results show that absolute permeabilities decrease when pore pressure declines during reservoir depletion. This permeability drop is not negligible. It’s equal to 15% for F1 rock-type and more than 50% for F2 rock-type. Pore volume change may be a non-negligible source of permeability change if the deformation is elasto-plastic. Because permeability reduction is well correlated to porosity change, experimental results are used to derive behavior law relating permeability reduction to porosity decrease (deformation). The proposed relationship gives good fit when F1 rock-type is considered. In contrast this relationship is not that easy for F3 rock-type.

This study shows that permeability decrease when pore pressure declines is not negligible and must be taken in account when simulating production profiles. On the other hand, permeability change caused by deformation depends on stress path. So as to obtain representative measurements, we suggest that laboratory tests must be carried out in conditions simulating real depletion.

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REFERENCES

1. ODA, N., TAKEMURA, T., AOKI, T., “Damage growth and permeability change in triaxial compaction tests of Inada granite”, Mechanics of Materials, (Jun 2002).

2. ZHU, W., WONG, T. F., MONTESI, L. G. J., “Shear-enhanced compaction and permeability reduction: triaxial extension tests on porous sandstone”, Mechanics of Materials, (Apr 1997).

3. TEUFEL W., “Permeability changes during shear deformation of fractured rock”, 28 U. S Symposium on rock mechanics}, (Tucson, 1997).

4. JAUMOUILLE L., CORDELIER Ph., KHARROUBI A., (1995) “Measurement of gas permeabilities under different compaction modes on tight reservoir samples”, (SCA 1995, paper N° 9519)

5. BOUTECA J. M., BARY D., PIAU J. M., KESSLER N., BOISSON M., FOURMAINTRAUX D., (1994) “Contribution of poro-elasticity to reservoir engineering: Lab experiments, application to core decompression and implication in HP/HT reservoirs depletion”, (Eurock, Delft 1994)

6. GRAY K.E., JOGL P. N., MORITA N., SROUJL F. A., “Rock property changes during reservoir compaction”, S.P.E Formation Evaluation, (September 1992)

7. RHETT D. W., TEUFEL L. W., “Effect of reservoir stress path on compressibility and permeability of sandstones”, 4th North Sea chalk symposium, Deauville (France, 1992)

8. STORMONT J. C., DAEMEN J. J. R., (1992) “Laboratory study of gas permeability changes in rock salt during deformation”, I. J. Rock Mech. Mining (1992)

9. TEUFEL L. W., & RHETT D. W., “Effect of reservoir path on permeability of fractures in chalk”, 4th North Sea Chalk Symposium, Deauville (France, 1992)