A FAST AND DIRECT METHOD OF PERMEABILITY MEASUREMENT ON DRILL CUTTINGS

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ABSTRACT

Permeability is one of the most important petrophysical parameters for reservoir characterization, but the most difficult to obtain. Logs provide a good estimate of porosity and saturations, but the accuracy on permeability derived from NMR is rather poor. So far, reliable permeability values are only obtained from laboratory measurements on core samples for local measurements and well testing for a larger scale averaged determination.

We present an original method for measuring the permeability of drill cuttings without any specific laboratory conditioning (cleaning, coating, etc.). A volume of about 100 cc of cuttings is placed in a pressure vessel. The cell is then filled with a viscous oil. The process of oil invasion into the cuttings always traps a certain amount of gas. When a pulse of pressure is applied on the cell, the oil enters the cuttings thanks to the gas compressibility. The permeability is then derived from the oil invasion dynamics using a simple model.

The method was tested using various samples of crushed rock samples of known permeability. An excellent reproducibility and a good agreement between cores and cuttings permeabilities were found for many decades of permeabilities. This method presents many advantages. The measurements can be performed in a few minutes, leading to the possibility of operating on-site during drilling. The limitations of the method are mainly related to the size and the representativity of the drill cuttings.

In developing this method, our purpose is not to replace core analysis, but rather to provide additional cheap and quick information on reservoir characterization prior to coring.

INTRODUCTION

When a new well is drilled, the main concerns of operating companies is to answer quickly two key questions: what are the reserves (porosity, saturation) and what is the well deliverability (permeability)? Most of the time, the logs provide a good estimate of porosity and saturations along the well. In this paper, we will focus on the evaluation of the permeability profile, which is much more difficult to obtain because this parameter refers to a flowing property of the reservoir rock. We present an original method to perform a direct measurement of permeability from cuttings, which may be suitable during the drilling operation.

Routine Analysis for Permeability

Core analysis in the laboratory is the most reliable technique to measure permeability but it is rather expensive (coring, rig time, transportation, measurement). The data are available several weeks after drilling. Well testing provides information on the extension and the connectivity of the reservoir and gives an average permeability value. A more accurate permeability profile can also be obtained with the MDT technique (Modular Dynamics Tester), run with wireline, with a spatial resolution of the order of the meter. NMR logging is now widely used to derive a fast evaluation of the permeability profile along the wells. However, the NMR tool is sensitive to the pore size whereas permeability is sensitive to throat size. Hence, the permeability evaluation is obtained through empirical laws, which

need to be calibrated according to the reservoir rock and also the fluids in place [3] (Fleury 2001).

Routine Cuttings Analysis

The cuttings are routinely used by the mudloggers to build the "masterlog", where the geological description of the drilled formation is reported. Hydrocarbon indices are also detected from cuttings to identify the reservoir levels. Although the cuttings rock material is coming directly from the reservoir, few applications of permeability characterization are reported in the literature. The published works can be divided into two categories: the direct and indirect evaluation.

Direct Permeability Evaluation Methods from Cuttings

Only one method is proposed in the classical range of hydrocarbon reservoir permeability[11] (Santarelli et al. 1998). The effective flow into the rock is achieved by embedding the cuttings in acrylic resin disks. The disks are then surfaced and mounted in a core holder to measure the permeability under constant-flow or transient-flow technique. Another method was proposed by Luffel[9] (1993) which is based on pressure diffusion. The cleaned and dried cuttings are introduced into a cell at atmospheric pressure. Then, the cell is put in communication with another cell under pressure and the decrease of the pressure is recorded and interpreted in terms of permeability. The principle is similar to well testing, using gas instead of liquids. However, due to the low viscosity of gases, this method can only be used on very low permeabilities (≤ 0.01 md).

Indirect Permeability Evaluation Methods from Cuttings

The permeability is derived using empirical correlations with properties related to pore size distribution, pore connectivity or the spatial correlation between the pores. These parameters are evaluated from capillary properties (mercury porosimetry), by NMR or image analysis.

Several approaches have been proposed to derive permeability from mercury porosimetry curves [6,11,13,14,15] (Purcell 1949; Thomeer 1960; Swanson 1981; Thomeer 1983; Katz and Thompson 1986). Kamath[5] performed a comparison between these methods and concluded that the best result is obtained with new correlations based on the Swanson characteristic length (Kamath 1992). Kamath and Swanson also reported a possible use of mercury porosimetry curves obtained from cuttings.

Many papers have been published on the permeability evaluation from NMR measurements, but very few refer to application on cuttings. In this domain, the main effort was conducted by Chevron in association with Exlog. They developed a prototype fitted for rig conditions[10] (Nigh and Taylor 1985). The cuttings are first prepared (cleaning, drying) and placed in a portable NMR tool. The porosity value is derived from the measured volume of water and the permeability is evaluated from the whole T_2 relaxation signal using the Timur law[16] (Timur 1968).

A thin section can also be obtained from cuttings to evaluate the porosity and the permeability from image analysis. The porosity corresponds to the void fraction whereas the permeability is derived from empirical laws[1,4] (Coskun and Wardlaw 1993; Ioannidis et al. 1996) or from Carman-Kozeny type laws[2,17] (Tomutsa and Brinkmeyer 1990; Fens et al. 1998).

In this paper, we present an original method to perform a direct measurement of permeability from cuttings. An effective flow of viscous oil is achieved by compression of residual gas initially trapped in the cuttings and the test is interpreted in terms of permeability with a numerical code. The first part is devoted to the presentation of the method, especially its

originality and advantages. Then, the experimental set-up for data acquisition, the procedures and the results are presented. The next section describes the physical model and the numerical calculation. Finally, the method is validated by comparisons with measurements made on crushed cores of known permeability for various sizes of cuttings. The results and the applicability of the method in the field are discussed in the last part.

PRINCIPLE OF THE METHOD

The problem is to establish a flow in the rock itself rather than in inter-cuttings space. AGIP method uses an acrylic resin to embed the cuttings and force the flow through the rock but it requires specific conditioning. In the proposed method, the flow is obtained by compression of residual gas initially trapped in the cuttings. A viscous oil is used as displacing fluid to minimize the diffusion coefficient of pressure into the rock.

Our method is close to the one proposed by Luffel[9] (1993) as both use pressure diffusion. To be applicable, the fluid used must be compressible and the mobility (k/μ) must be small enough to have an impact on the pressure regime. As Luffel[9] (1993) used gas, only low permeability rocks can be measured (<0.01 md). The extension of the method to higher permeabilities requires fluids with higher viscosity like liquids. But they are not suitable in terms of compressibility. The originality of our method is to combine a viscous oil (from 200 to 1200 cP) for pressure drop and a gas for compressibility. We have tested several methods[8] (Lenormand and Egermann 2000, 2002), but we will present only the constant injection pressure procedure which gives the best results.

EXPERIMENTAL APPROACH

In this part, we describe the experimental set-up, the procedures and the results obtained using the proposed technique.

Experimental Set-up

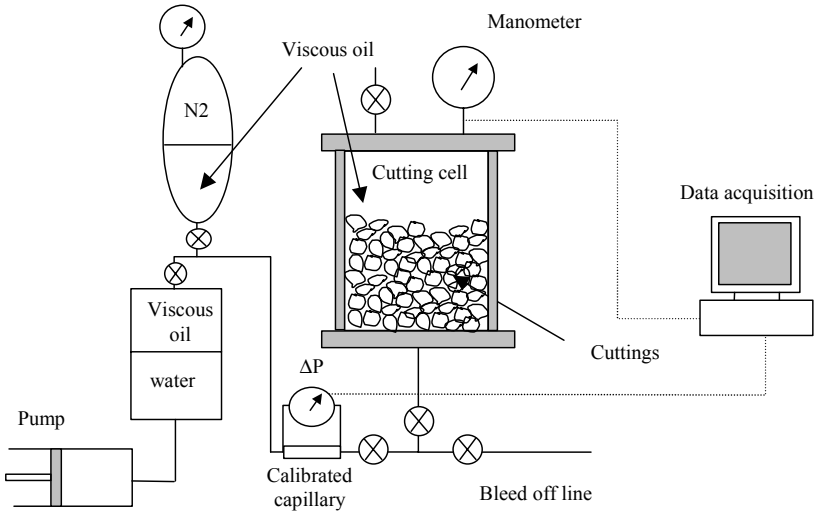

Figure 1: Experimental apparatus

The experimental apparatus is very simple (Figure 1). It is mainly composed of a cell, where the cuttings are introduced and a pump to inject the viscous oil. Due to its high viscosity, the oil is not directly injected by the pump but pushed by water. Another cell is filled with the viscous oil and nitrogen at constant pressure. A differential pressure sensor is mounted

between the two ends of a calibrated capillary tube between the cuttings cell and the constant pressure reservoir. A calibration curve, obtained from injections with the pump, is used to convert the pressure into flow rates. The volume of oil which enters the cuttings cell is obtained by numerical integration of the flow rate. All the data are automatically recorded on a computer at a frequency of 500 Hz to follow the sharp pressure variations.

Procedures

Initially, the cuttings are introduced into the cell which is filled with helium. The advantage of helium is to present a very low dissolution coefficient in oil in order to limit the dissolution of the residual gas when the pressure of the system is increased. The sealing of the cuttings cell is carefully checked before each experiment by a pressure test at 10 bars. If no leak is detected, the pressure is dropped down to atmospheric and the system is filled with the viscous oil using the pump and the transfer cell. The injected oil displaces the gas located in the inter-cuttings space and also invades the cuttings by spontaneous imbibition. The gas expelled from the cell and the rock is produced upwards. The duration of this period depends on the rock properties (mainly its porosity). Generally, the cuttings are saturated within one hour. At the end of this period, helium is trapped inside the cuttings as residual, disconnected gas. The test is ready to be done.

Initially, the cuttings cell is at atmospheric pressure and isolated by the valves at the top and at the bottom. The pressure in the nitrogen is set to 10 bars. Then, the bottom valve of the cuttings cell is opened and viscous oil is injected due to the pressure difference . The rate of oil entering the cell and the pressure in the cell are recorded.

The number of cuttings introduced into the cell is evaluated before each test by weighting. The weight of 100 cuttings is first measured several times. Then, the total number of cuttings is derived from the total weight of cuttings introduced. The temperature is also recorded before each test in order to take into account the effective value of the oil viscosity. These two parameters need to be carefully evaluated because they have a major impact on the accuracy of measurement.

Results

An example of experimental results is plotted in Figure 2. Initially, the pressure drop though the capillary tube is maximum, which corresponds to a very high injection rate (36 liter/hr). Then, the pressure drop decreases but does not return to zero immediately due to the time needed for pressure to be balanced inside the cuttings and to compress the trapped gas. When the pressure drop is converted into injected volume, two main periods can be distinguished. The first one is short (around 0.5 second) and corresponds to a fast filling of the cuttings cell at a quasi constant injection rate (linear evolution of the injected volume). The cell pressure increases very quickly from zero to 10 bars (injection pressure). This period is followed by a stabilization period, where the injected volume converges towards an equilibrium value. During this period, the cell pressure remains roughly constant, equal to the injection pressure. In terms of boundary conditions, we can then consider that the filling of the cuttings can be represented by a constant injection rate period followed by a constant pressure injection period.

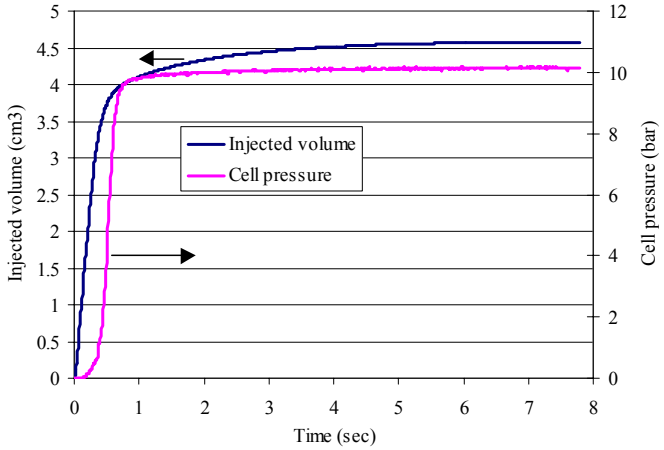

Figure 2:Experimental cell pressure and injected volume as a function of time

Several tests were performed on cuttings obtained by crushing core samples of known permeability. Different types of rock were used to cover a wide range of permeability from 0.1 md to 2000 md (Table 1). The first tests were run with large cuttings (3-5 mm) in order to develop the experimental procedures and the interpretation tool. Then, additional tests were performed with 2-3 mm and 1-2 mm cuttings sizes to explore the sensitivity of the method.

Table 1: Constant pressure injection experiments

Rock name	**k core md**	**ϕ core %**
Tu	1.7	11.5
Lavoux	4	25.2
Palatinat	8	20.8
Rot8	222	22.1
C4	450	17.7
D3	0.14	12
B6	80	26.3
GDV1	190	23.9
StMax	1700	39.2

The results of the tests run with a 3-5 mm cuttings size are plotted in Figure 3. The shape of the oil injection curves varies significantly depending on the nature of the rock material tested. First of all, the cumulated volume of oil injected differs. This feature is directly related to the quantity of gas trapped in the cuttings cell initially. As the initial trapped gas is strongly correlated with the rock pore volume, the less porous cuttings correspond to the low curves (Tru, Palatinat). Large differences are also observed in terms of stabilization kinetics. The volume of oil injected tends to converge faster for high permeability cuttings (StMax, B6), whereas it can take more than 10 seconds for the signal to converge for low permeability cuttings (Tru).

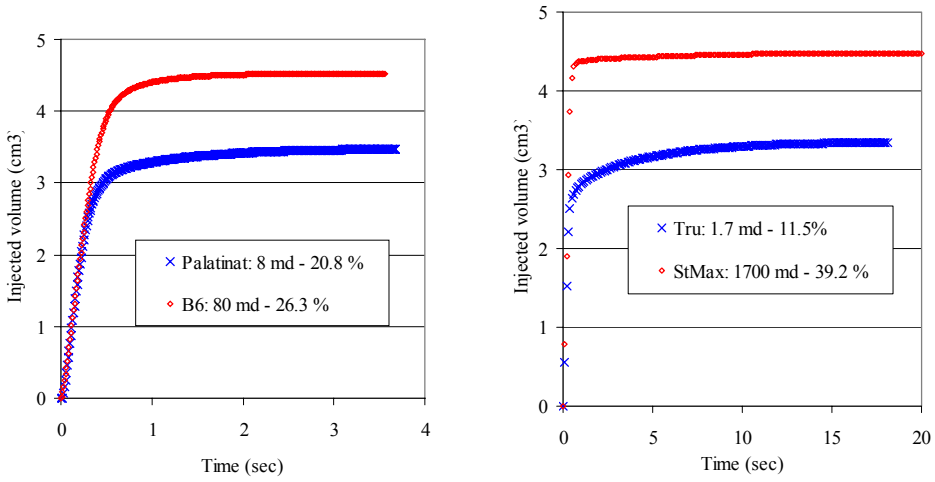

Figure 3: Constant pressure injection tests (3-5 mm)

These results show that we observe qualitatively a strong difference in terms of kinetics and amplitude of oil filling depending on the petrophysical properties of the rock material tested (mainly porosity and permeability). These trends will be further explored by a quantitative identification using the numerical tool that is developed in the next part (history matching).

MODELLING

Assumptions

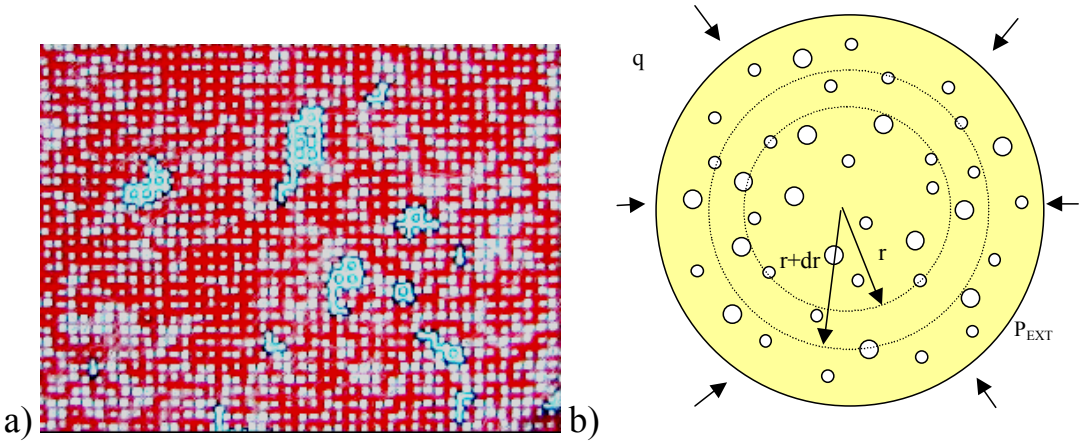

Figure 4: Micromodel experiment showing the trapped gas and model used for calculation

The model used to calculate the permeability is based on the following assumptions:

- The cuttings are uniform in size. The uniformity is controlled by a preliminary screening (3-5 mm, 2-3 mm and 1-2 mm).
- The cuttings are spherical. Usually, the aspect ratio is close to 1, which justifies this assumption.
- The gas follows the perfect gas law.
- The residual gas after imbibition is disconnected as ganglia homogeneously distributed in the rock volume as illustrated with a micromodel experiment (Figure 4a)
- The gas remains immobile because it is already trapped and disconnected.

- The Darcy law applies inside the cuttings. Several works have established that a size of the order of 1 mm is large enough to consider an elementary representative volume[7] (Larson and Morrow 1981).
- The capillary pressure is not taken into account

Using these assumptions, we can write the mass balance and pressure equations in an elementary cuttings as shown in Figure 4b. We use spherical coordinates and make the calculation in a portion of the sphere of thickness dr.

Pressure Diffusion Equation

Applying the perfect gas law enables to deduce the gas saturation value as a function of the local pressure and the initial gas saturation.

$$S_g = S_{g0}\frac{P_0}{P} \tag{1}$$

In the elementary portion of the sphere, a standard mass balance leads to

$$\mathrm{div}\vec{V}_o + \phi\frac{\partial S_0}{\partial t} = 0 \tag{2}$$

Oil saturation is written as function of gas saturation

$$S_o = (1 - S_g) = (1 - S_{g0}\frac{P_0}{P})$$

we derive,

$$\frac{\partial S_o}{\partial t} = \frac{\partial S_o}{\partial P}\frac{\partial P}{\partial t} = \left(S_{g0}\frac{P_0}{P^2}\right)\frac{\partial P}{\partial t}$$

From Darcy's law,

$$\vec{V}_o = -\frac{K}{\mu_o}\vec{\mathrm{grad}}P_{oil} \tag{3}$$

Without capillary pressure, we get $\Delta P = \frac{\mu_o \phi S_{g0}}{K}\frac{P_0}{P^2}\frac{\partial P}{\partial t}$, which can be also written in spherical coordinates :

$$\frac{\partial}{\partial r}\left(r^2\frac{\partial P}{\partial r}\right) = \alpha\frac{r^2}{P^2}\frac{\partial P}{\partial t} \qquad \text{with} \qquad \alpha = \frac{\mu_o \phi S_{g0} P_0}{K} \tag{4}$$

Finally, we obtain a pressure diffusion equation weighted by S_{g0} and a factor $1/P^2$ due to the gas compressibility. The above equation can be written in dimensionless form using the following variables (*):

$$P^* = \frac{P}{P_0} \qquad r^* = \frac{r}{r_{max}} \qquad t^* = \frac{t \times D}{r_{max}^2}$$

with $D = \frac{K \times P_0}{\phi \times S_{g0} \times \mu}$, the pressure diffusion coefficient at P_0.

Finally, we obtain

$$\frac{1}{r^{*2}}\frac{\partial}{\partial r^*}\left(r^{*2}\frac{\partial P^*}{\partial r^*}\right)=\frac{1}{P^{*2}}\frac{\partial P^*}{\partial t^*} \qquad (5)$$

It has to be pointed out that K normally corresponds to the oil permeability at the trapped gas saturation. As the cuttings are compressed to 10 bars during the experiment, the trapped gas saturation behind the pressure diffusion front is very small so that we have considered that the effective oil permeability is practically equal to the absolute permeability.

Numerical Calculation

The experimental results showed that two main periods exist. These periods correspond to specific boundary conditions. A constant injection rate period is observed during the early times of the experiment followed by a constant injection pressure period for the longer times.

First Period at Constant Injection Rate

During the first period, the elementary injection rate per cutting is known (q=Q/Nc) and the pressure outside the cutting (Pext) has to be found.

Boundary conditions:

Time: $P(r,0)=1$ Space: $\frac{\partial P}{\partial r}(0,t)=0$ and $P(1,t)=P_{ext}$

The value of P_{ext} is deduced from a loop of convergence detailed in Figure 5. We start the resolution by a default value of P_{ext}, which permits the calculation of the pressure profile inside the cuttings. From the pressure profile, the saturation profile is deduced and then the volume of oil injected needed to compress the gas. This volume is compared to the volume effectively injected according to the injection rate ($q \times t$), which enables to correct the value of P_{ext} according to the results.

The above equation (5) was solved using a finite difference technique with explicit scheme in time and space.

Second Period at Constant Injection Pressure

When P_{ext} reaches the value of the nitrogen pressure used to inject the oil, then the boundary condition is changed and P_{ext} is kept equal to P_{N2}. The pressure profile can then be calculated straight forward from the pressure diffusion equation. The corresponding volume of oil injected during this period can be easily derived from the gas saturation profile.

An illustration of the numerical resolution can be found in Figure 6a. The first period is very short (0.4 - 0.5 second) and corresponds to a fast increase of the pressure inside the cuttings cell (P_{ext}). When the pressure reaches the nitrogen pressure (11 bars), the code changes its boundary condition and a flattening of the volume of oil injected curve is observed. These numerical results are in very good agreement with our experimental observations (Figure 2).The influence of the cuttings permeability on the shape of the oil injected curve can be found in Figure 6b. As observed experimentally, the stabilization kinetics decreases when permeability decreases.

This numerical model has been modified to take into account the various experimental mechanisms that occur during the test:

- presence of a fraction of gas trapped in the inter-cuttings space,
- compressibility of the system (oil and the cell)
- dissolution of a fraction of the gas in the surrounding oil.

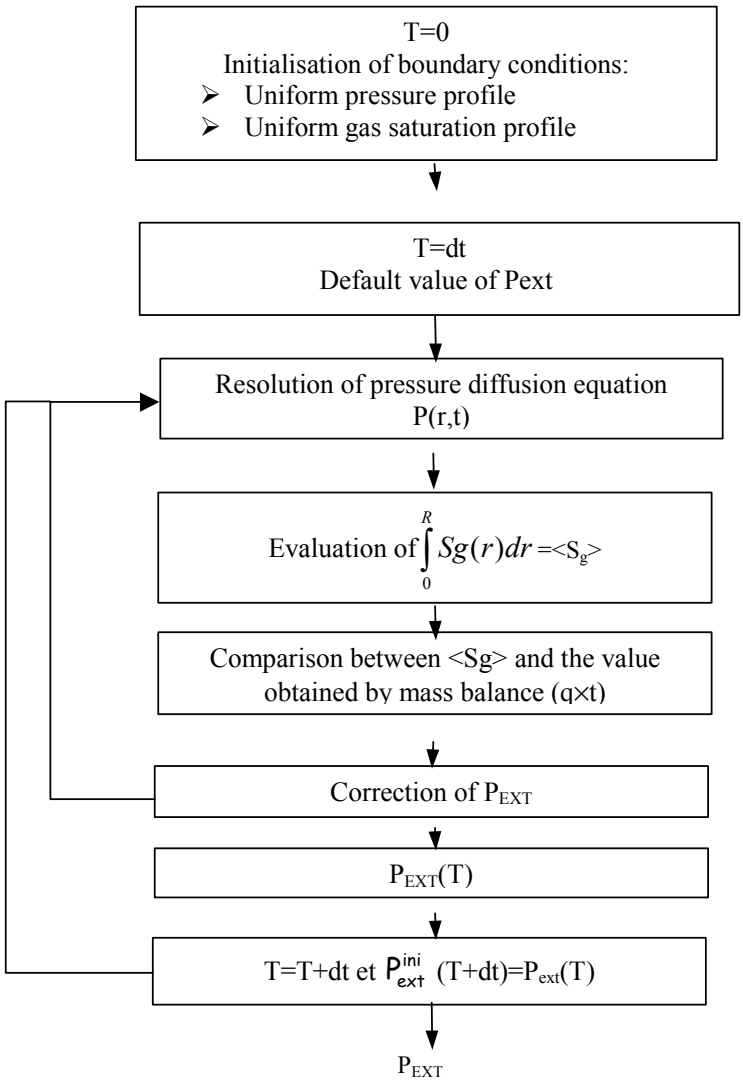

Figure 5: Loop of convergence for calculation of Pext (constant injection rate)

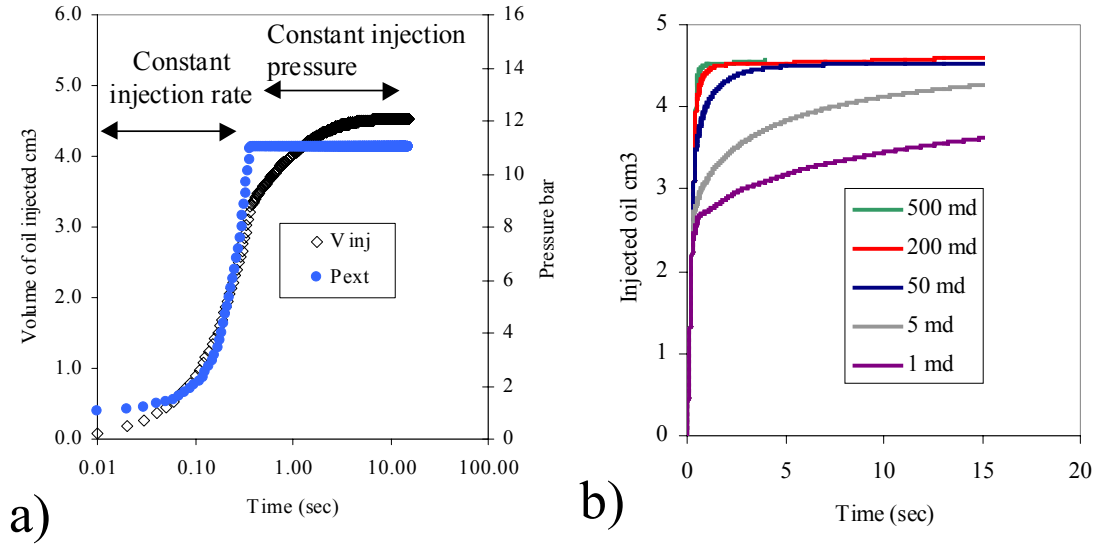

Figure 6: Numerical outputs of the interpretation tool

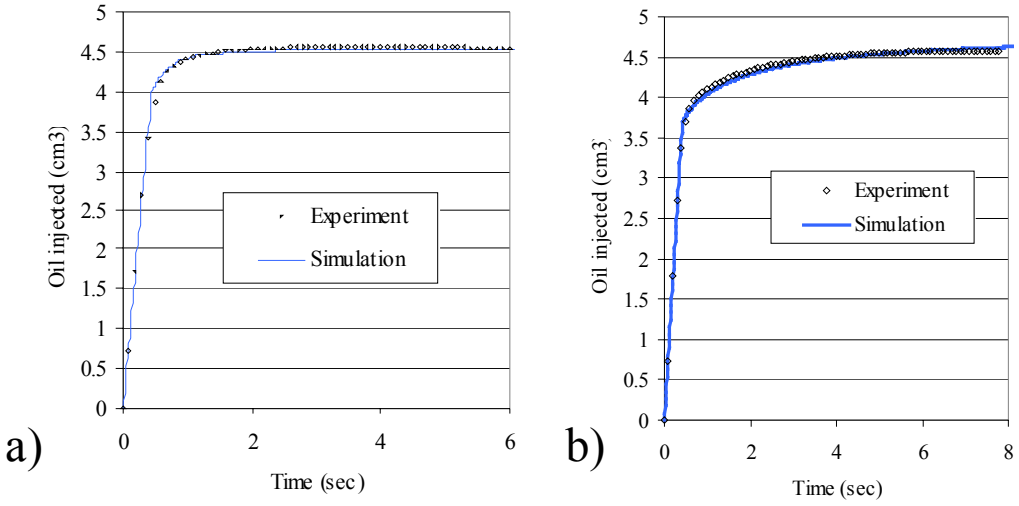

Figure 7: History matching of two experiments: a) Lavoux, b) B6

DISCUSSION

Validation on Crushed Core Cuttings

Two examples of history matching are provided in Figure 7 a and b. The agreement between the experimental data and the simulation is obtained very quickly with few iterations on the values of k and volume of initial gas ($\phi \times S_{g0}$ and V_{gt}, the trapped gas outside the cuttings). The value of S_{g0} was kept equal to 25% in all the simulations to enable a raw estimation of the porosity.

Figure 8a shows a very good agreement between the permeability values estimated from cuttings and the reference permeability measured on cores. For the largest cuttings size, we obtain a very good agreement on a wide permeability range (0.1 – 2000 md) whereas it is possible to run the measurement up to 200 md with 2-3 mm cuttings.

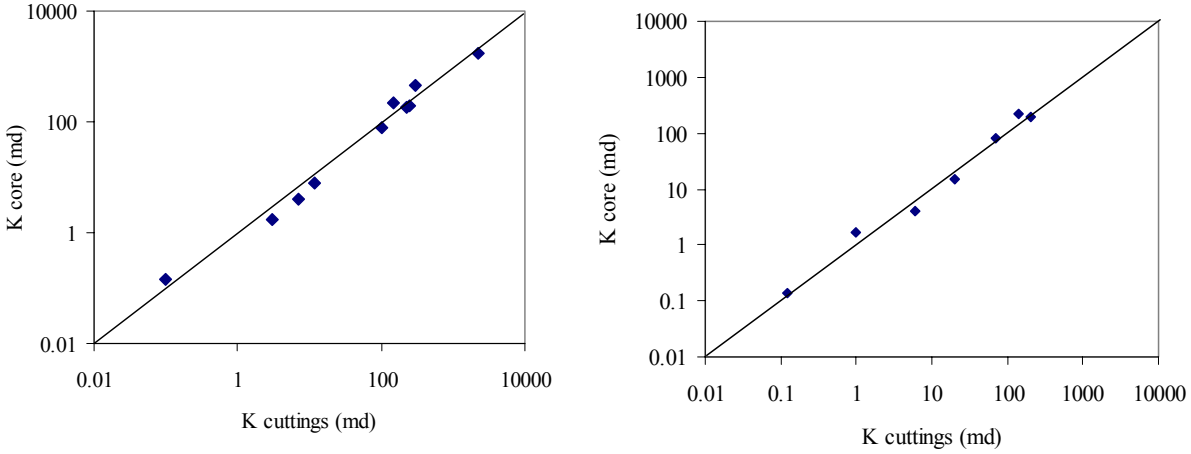

Figure 8: Comparison of core and cuttings permeabilities

Applicability of the Method in the Field

Compared to the existing approaches, the main advantages of the proposed method is a direct evaluation of permeability with a simple, fast and accurate measurement. Experimentally,

only one action is required to run the test: opening one valve. The interpretation of the test is also very easy to perform. Even if some gas remains trapped in the inter-cuttings space, the constant injection pressure procedure enables to compress it at the early times of the experiment. Hence, this gas does not affect the pressure diffusion process that occurs inside the cuttings for the longer times. This separation between the signal from the gas trapped inside and outside the cuttings makes the history match very consistent and easy to obtain. All these features make the proposed method very adapted to field application.

Currently, additional tests are performed with smaller cuttings (1-2 mm). The first results show that permeability values up to 50 md can be detected using the proposed method and this size of cuttings.

Sensitivity to the Porosity

Although the proposed methodology is not designed to estimate the porosity, Figure 9 demonstrates that a reasonable estimation of this parameter is obtained for most of the samples. The large variations that are observed in some cases certainly result from our assumption on the value of S_{g0} (25%), which may vary significantly depending on the rock.

CONCLUSIONS

A new methodology is proposed to measure the permeability directly from cuttings. An effective flow inside the cuttings is obtained by compression of residual gas initially trapped in the cuttings. A viscous oil is used as displacing fluid to decrease the pressure diffusion coefficient in the rock. The proposed method does not require specific conditioning, it is easy to handle and provides consistent results in the conventional reservoir permeability range (up to 2000 md for 3-5 mm cuttings, up to 200 md for 2-3 mm cuttings and up to 50 md for 1-2 mm cuttings). Due to its simplicity and its consistency, this method could be used in the field in order to provide a fast evaluation of the reservoir permeability in quasi real time during drilling. This study is part of a project devoted to the petrophysical characterization of reservoir from cuttings measurements (porosity, residual saturation, capillary pressure).

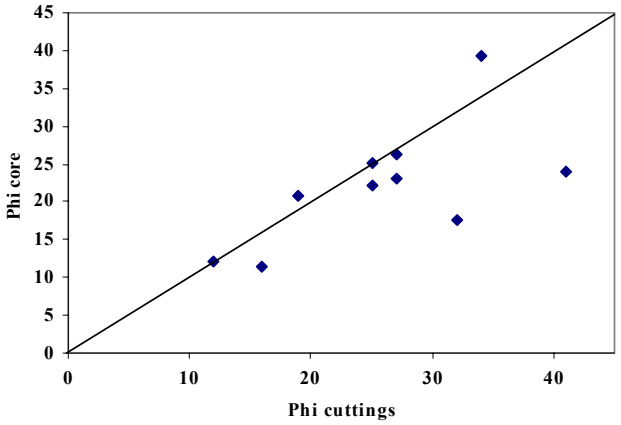

Figure 9: Porosity estimation (S_{g0}=25%)

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NOMENCLATURE

DP: pressure drop
K: permeability
μo: oil viscosity
ϕ: porosity
Nc: number of cuttings
P: pressure
P_{ext}: pressure at the cutting boundary
P_0: initial pressure
Q: total injection rate
q : elementary injection rate
Rmax: cutting radius
S_g: gas saturation
S_{g0}: initial gas saturation at P_0

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