THE "STEP DECAY": A NEW TRANSIENT METHOD FOR THE SIMULTANEOUS DETERMINATION OF INTRINSIC PERMEABILITY, KLINKENBERG COEFFICIENT AND POROSITY ON VERY TIGHT ROCKS

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ABSTRACT

Accurate determination of the intrinsic permeability k_l, Klinkenberg coefficient b and porosity Φ is of crucial importance to correctly characterize tight gas or gas shale reservoirs. So far, very few methods allow the simultaneous determination of these three parameters. Porosity is generally measured separately, by pycnometry or by weighing. This paper reviews some hidden pitfalls of the interpretation of the methods based on the analysis of pressure decay such as the Pulse Decay test to estimate k_l (and b).

Firstly, this paper shows that the estimated values of k_l and b are strongly influenced by 1) inaccuracies in Φ which is an input parameter required for the interpretation of the pressure transient; 2) inaccuracies in the determination of the upstream dead volume; 3) inaccuracies in the initial value of the pressure pulse due to a rapid gas expansion in the dead volume at valve opening, yielding pressure and temperature fluctuations at the beginning of the test. These issues are illustrated by numerical simulations and the most critical cases are highlighted.

Secondly, this paper proposes a new method, the "Step Decay" method that has two main strengths: 1) it gives k_l, b and Φ in one test only, speeding up the laboratory programs; 2) it removes all the difficulties listed above.

The key idea relies on the estimation of k_l, b and Φ from the downstream pressure response $P_1(t)$ resulting from a pressure signal $P_0(t)$ at the upstream. More precisely, both $P_0(t)$ and $P_1(t)$ are measured but $P_0(t)$ is taken as an experimental input datum of the interpretative model while $P_1(t)$ only is used to determine the medium properties by history matching. Consequently:

- Accuracy of the estimated values of k_l and b is insensitive to $P_0(t)$ irregularities, which might originate from pressure and temperature fluctuations or even gas leakage.
- The physical problem becomes independent of the upstream tank volume and hence, of the upstream dead volume.

- $P_0(t)$ can take any form, a feature that can be advantageously used to increase sensitivities of $P_1(t)$ to k_l, b and Φ for an improved estimation of these three parameters. Successive pulses are used giving the name of the Step Decay method.

Through several examples, we show that this method is robust over a very wide range of permeability, down to tens of nanodarcy, and porosity, including very compact rocks. These examples include tests on the same samples carried out in two different laboratories confirming the reproducibility of the measurements.

INTRODUCTION

Tight gas reservoirs and gas shales represent a promising resource for the next coming years. Due to their poor level of permeability, gas flow description in such formations must account for Klinkenberg effect yielding a common admitted pressure dependent apparent permeability $k = k_l(1 + b/P)$. However, the reliable determination of k_l, b and porosity, Φ from laboratory-scale experiments remains a challenging task, as testified by the countless studies reported on the subject over the past decades. Currently, virtually no method enables the simultaneous characterization of these three parameters. Indeed, Φ is usually measured separately by means of a pycnometry or a weighing test, often under stress conditions different from those of the permeability measurement. A rapid overview on the reported results on k_l and b measurements also indicate a large discrepancy from one laboratory to another (sometimes of more than an order of magnitude), suggesting to carefully re-inspect the measurement methods, and try to improve them.

Common steady-state methods to perform permeability measurements on core plugs have been used until recently (Rushing *et al.* [1]). While porosity must be measured independently, the major drawback of such methods, however, lies in the separate estimation of k_l and b requiring a series of different experiments carried out at sufficiently contrasted mean pressures. This can be an extremely long process in practice, from a few hours to even days, when samples are very tight as the time required to reach steady-state, at each new measuring point, is inversely proportional to k_l. Thus, alternative methods are of particular interest for the characterization of ultra-low permeabilities.

In the early 50's, Bruce *et al.* [2] proposed an unsteady-state method, referred to as "Pulse Decay". Typically, an unsteady-state test consists in applying a pressure increment at the upstream sample edge to produce a pressure gradient. The interpretation of the pressure drop evolution across the sample allows the determination of the properties, restricted to k_l only in most of existing works. In the analysis of Bruce *et al.*, the Klinkenberg effects were not considered in the interpretative physical model and no procedure was provided to estimate k_l. This pioneering work gave birth to numerous other studies on the method.

Shortly after Bruce *et al.*, Aronofsky *et al.* [3] elaborated an approximate technique to identify k_l, b and Φ empirically, using three different experiments, leading to a rather complex protocol and a series of approximations which impact on the interpretation is difficult to quantify. Almost a decade later, Brace *et al.* [4] derived an approximate model to interpret the recorded pressure decay signal based on the assumption that the capacitive (porosity) effects caused by gas accumulation in the pores can be ignored. This is equivalent to supposing that Φ=0 or that the flowing gas density is time independent. Only k_l is deduced from this approach. Jones [5] popularized the method and improved the work of Brace *et al.* by including the Klinkenberg (and Forchheimer) effects in the model. An approximate iterative method was proposed in this work to partially relax the hypothesis of a constant gas density. However, Jones' model still does not allow the estimation of Φ and the consequence of the approximation in the interpretation remains unclear in the general case. Several authors stressed that ignoring Φ can originate substantial errors (Trimmer [6], Newberg and Arastoopour [7]). Since Jone's work, the method has nevertheless been extensively used over the years.

When Klinkenberg and/or capacitive effects are neglected, an analytical solution to the initial boundary value problem describing the pressure evolution along the sample (including its edges) can be found as reported in many references. After Jones' attempt to derive a quasi-analytical solution (recently reformulated by Kaczmarek [8]) Hsieh *et al.* [9] developed a solution under the form of a series enabling a graphical identification of the apparent permeability, k, and storage coefficient (porosity corrected by compressibility effects). Assuming that the upstream pressure remains constant over time, Bourbie [10] obtained a solution given by combinations of the error function. When all these hypotheses are removed, no analytical solution is available.

To summarize, most existing works on unsteady methods aim at estimating k or k_l separately from Φ and generally, without heeding b. The only few ones enabling the characterization of k or k_l and Φ by carrying out a single experiment are always based on approximations which consequences on the method reliability are difficult to appraise. Furthermore, the various protocols developed until now are time consuming, often difficult to carry out in practice and quite never executed under optimal conditions from the viewpoint of the estimation of the sample properties. More recently, Jannot and Lasseux [11] proposed an alternative quasi-steady method to determine k_l and b.

In the present work, a more systematic way of interpreting a Pulse Decay experiment, with simplifying assumptions reduced to a minimum, is first recalled along with the optimal configuration for such an experiment (see Jannot *et al.* [12, 13]). On this basis, we show that the technique still conceals hidden pitfalls. To circumvent these difficulties, a new method, referred to as the Step-Decay, is detailed allowing the simultaneous determination of k_l, b and Φ. The robustness of the method is illustrated over wide ranges of k_l, b and Φ. Experimental results, that were successfully cross-compared from measurements carried out independently on the same samples in two different laboratories, are reported

DRAWBACKS OF THE EXISTING METHODS

In recent SCA papers, Jannot *et al.* [12, 13] presented a detailed analysis of the Pulse Decay technique, without making any particular simplifying assumptions out of the basic ones including a rigid porous matrix and a weakly compressible isothermal creeping gas flow. The corresponding physical model is given by

$$\frac{\partial^2 \phi}{\partial x^2} = \frac{\alpha}{\sqrt{\phi}} \frac{\partial \phi}{\partial t}, \qquad \alpha = \frac{\Phi \mu}{k_l}, \qquad \phi = \left(P + b\right)^2 \tag{1}$$

$$\phi(0,0) = (P_{0i} + b)^2, \qquad \phi(x,0) = (P_{1i} + b)^2 \text{ for } x>0 \tag{2}$$

The associated boundary conditions at the entrance (x=0) and exit (x=L) faces of the sample are

$$\frac{\partial \phi}{\partial t}(0,t) = \frac{k_l\, S}{\mu\, V_0}\left(\sqrt{\phi}\,\frac{\partial \phi}{\partial x}\right)_{(0,t)} \qquad S = \pi\, D^2/4 \tag{3}$$

$$\frac{\partial \phi}{\partial t}(L,t) = -\frac{k_l\, S}{\mu\, V_1}\left(\sqrt{\phi}\,\frac{\partial \phi}{\partial x}\right)_{(L,t)} \tag{4}$$

Since no analytical solution to this complete model is available, an inverse procedure must be employed so as to identify the optimal parameters k_l and b that minimize, in the least square sense, the measured pressure drop signal $P_0(t)$-$P_1(t)$. This history matching procedure, performed with a Levenberg-Marquardt algorithm, was reported in [13, 14]. It makes use of a direct numerical solution to Eqs (1) through (4) based on a finite difference scheme, the key controlling data being P_{0i}, the initial upstream pressure generating the pulse and P_{1i}, the initial sample equilibrium pressure. On this basis, Jannot *et al.* [12] performed a sensitivity analysis which purpose was to determine the optimal experimental conditions ensuring the most accurate estimation of the properties. The impact on k_l and b identified by history matching due to bias on the different parameters intervening in the interpretative model was further assessed by Jannot *et al.* [13]. Major results emerged from these works. First of all, it was demonstrated that, to guarantee the best estimation of k_l and b, the Pulse Decay test must be performed with V_1 infinite (i.e. by leaving the sample outlet face open to atmosphere) corresponding to a so-called Draw-Down configuration. History matching is hence carried out on the pressure decay $P_0(t)$. In addition, since sensitivity of $P_0(t)$ to Φ is poor and restricted to the early part of the signal, this parameter can not be reasonably estimated by history matching simultaneously with k_l and b.

Secondly, the bias analysis showed that:

- an error on porosity, that is an input parameter for history matching, has a very important impact on estimated values of k_l and b;
- a dead volume DV, initially at P_{1i}, always present between the sample inlet face and the valve v_0 isolating the upstream tank V_0 (see Figure 3 for DV, v_0 and V_0), must be carefully measured and integrated in the interpretation as it strongly affects the estimated values of k_l and b.

Moreover, opening v_0 induces a rapid expansion of the gas from V_0 to V_0+DV, entailing temperature and pressure fluctuations in V_0. The consequence of this is twofold: first it confirms that Φ can not be reliably extracted from the history matching on $P_0(t)$ since sensitivity to this parameter is restricted to the early period of $P_0(t)$ which turns to be perturbed by these fluctuations. Second, the actual value of P_{0i} is blurred whereas this value is a key input parameter to estimate k_l and b. The impact of DV and of a bias on both Φ and P_{0i} are now highlighted.

To illustrate the impact of a bias on Φ, a synthetic test was carried out on a Test Material (TM) having the following characteristics: k_l=0.1 µD, b=13.08 bar, Φ=0.01, D=L=5 cm while the other physical parameters were chosen as: P_{0i}=35 bar, P_{1i}=1 bar, V_0=10 cm^3,

μ=1.8 10^{-5} Pa.s. The synthetic signal was generated from the direct numerical solution mentioned above with a number of time steps NP=10^4 and a number of space nodes m=100 in the Draw-Down configuration. To be more representative of a real pressure decay record, a Gaussian noise was superimposed to the synthetic signal. This noise is given by $\delta P = 0.01\, dP\, s\, P_{0i}/3$ where s is a random number of unit standard deviation and dP is the error on $P_0(t)$ (in % of the measurement). The coefficient 3 was taken so that $P_0(t) \pm \delta P$ includes 99.7% of the noisy values if they would have been actually measured. Here, we chose dP=0.1. The signal was simulated with the nominal values of Φ in the Draw-Down configuration up to t_f=5400 s (90 mins). History matching was then carried out on the synthetic signal with a slightly modified value of Φ: $\Phi \pm \delta\Phi$, with $\delta\Phi$ =20%, a reasonable value considering the value of Φ. Estimated values of the parameters and their relative errors are reported in Table 1.

Results listed in this table clearly show that uncertainty on the porosity measurement drastically alters the accuracy of the estimated values of k_l and b, with a more pronounced effect on b. The resulting errors on these parameters are definitely unacceptable.

A similar procedure was adopted to illustrate the impact of the presence of a dead volume DV. A signal was simulated first, in the Draw Down configuration accounting for DV, which implies that both V_0 and P_{0i} must be corrected for the direct simulation according to: $(V_0)_{corr} = V_0 + DV$ and $(P_{0i})_{corr} = (P_{0i}\, V_0 + DV\, P_{1i})/(V_0 + DV)$ where the subscript 'corr' stands for 'corrected'. The value of DV was chosen as DV=0.075 cm^3 (i.e. 0.75% of V_0 or equivalently a volume of approximately 3.1 cm of a 1/8" Swagelok® tubing), yielding $(P_{0i})_{corr} \approx 34.75$ bar. Values for all the other parameters were those used above to illustrate the bias on Φ. Then, the signal was inverted by neglecting the dead volume in the interpretation, i.e. by using the nominal values of V_0 and P_{0i}. Estimated values of k_l and b are reported in Table 2 along with the corresponding relative errors. Again, errors induced on the estimated values of k_l and b are very large, confirming that the presence of an upstream dead volume, even small compared to V_0, may drastically affects the estimated values of k_l and b: a dead volume, less than 1 % of V_0 only, produces errors of roughly 80% and 100 % on k_l and b respectively in the case under consideration.

The same synthetic pressure decay recording was employed to appraise furthermore the effect of a bias on P_{0i} on the accuracy of k_l and b estimates. To do so, history matching was carried out by keeping V_0 at its corrected value while P_{0i} was taken at its nominal value, leading to a bias of roughly 0.72% on P_{0i}. Results of history matching are also gathered in Table 2.

This test explicitly shows that a bias on P_{0i}, has a considerable impact on k_l and b estimates (about 87% on k_l and 99% on b in the present case). Owing to this significant sensitivity of k_l and b to the accuracy on P_{0i}, which is clearly limited by perturbations occurring at the pulse emission, Finsterle and Persoff [15] even proposed to estimate this parameter in addition to the medium properties. This seems however compromised considering the fact that the bias on Φ might considerably impact the estimation of P_{0i} having even a more dramatic consequence on the estimation of k_l and b.

Last but not least, a leak in the upstream gas circuit (which is the high pressure part of the setup), even small, might significantly affect the estimated values of k_l and b (it would be lumped into the gas flux through the sample), especially while dealing with small values of k_l as those under concern for tight or shale formations. In addition a bias on V_0 might also affect the result.

THE NEW METHOD: THE STEP DECAY

The classical Pulse-Decay, even when coupled to a history matching procedure that does not make uncontrollable simplifying assumptions in the physical model and even when carried out under optimal conditions with respect to the identification of k_l and b (i.e. in the Draw-Down configuration) clearly conceals pitfalls highlighted above. A more robust and complete method would be hence of considerable interest. A step ahead can be made with the new technique described below.

To remove the sensitivity of the estimated parameters k_l and b to the upstream dead volume, bias on P_{0i} and possible leak at the upstream, the idea consists in no longer considering the initial pulse value P_{0i}, from which $P_0(t)$, is computed as the unique datum. Rather, we shall reintroduce a downstream tank of finite volume V_1 and consider two separate time data records: $P_0(t)$ and $P_1(t)$. The pressure decay $P_0(t)$ is now used as an input in the history matching procedure, i.e. the boundary condition (3) is now replaced by a Dirichlet condition $P(0,t)=P_0(t)$, $P_0(t)$ being the upstream pressure decay that is actually measured. The history matching is now carried out on the downstream pressure build-up $P_1(t)$. In essence, the method consists in identifying the physical parameters of the sample subjected to the excitation $P_0(t)$ that yields a response $P_1(t)$. Many advantages derive from this procedure. Indeed, since $P_0(t)$ is no longer simulated but considered as an input datum, it may contain any kind of irregularities resulting from a dead volume, an upstream leak, etc. all artifacts which signature will anyway be reflected in $P_1(t)$. Bias on P_{0i} is no longer concerned since it is part of the input ($P_{0i}=P(0,0)$). Moreover, since the entrance boundary condition is $P(0,t)=P_0(t)$, the volume V_0 is no longer present in the model: its knowledge is not even necessary avoiding the effect of a possible bias on this parameter. The presence of the dead volume can be totally ignored as well.

To make the method more effective, the idea is to identify Φ, simultaneously with k_l and b from $P_1(t)$. However, since porosity is related to gas accumulation in the pores (a capacitive mechanism, i.e. a "short-time" effect), the sensitivity of $P_1(t)$ to Φ may remain small and anyway restricted to the very early stage of the pressure build-up, making the identification of Φ unreliable. This is illustrated in Figure 1.a where we have represented the reduced sensitivities of $P_1(t)$, $Sk_1 = k_1\,\partial P_1(t)/\partial k_1$, $Sb = b\,\partial P_1(t)/\partial b$ and $S\Phi = \Phi\,\partial P_1(t)/\partial \Phi$ to k_l, b and Φ as well as $Sk_1/S\Phi$. This was computed on the Test Material (TM) which characteristics were reported above, keeping V_0=100 cm^3, P_{0i}=35 bar, P_{1i}=1 bar, t_f=5400 s, N=10^4 and m=100 while V_1=10^3 cm^3. This figure clearly shows that the sensitivity of $P_1(t)$ to Φ is much smaller than those to k_l and b and becomes constant after roughly 700 s while during this period $P_1(t)$ increased by 9 mbar which is not significant enough for the estimation of Φ to be effective. Moreover, it can be noticed that the ratio of sensitivities to k_l and b becomes quasi constant after 2800 s, a period over which $P_1(t)$ has increased by roughly 55 mbar only, a variation that is really too small to carry out the estimation. This means that these two parameters appear to be correlated

after 2800 s in the history matching process making difficult their simultaneous identification. All these difficulties are however only apparent, despite the deliberate choice of a very large value for V_1. In fact, one can advantageously take benefit of this new method by noticing that $P_0(t)$ can be time modulated in any way that is convenient to improve sensitivities. In particular, $P_0(t)$ can be varied so as to repeatedly activate the capacitive behavior of the sample (i.e. generate multiple "short time" effects) improving $S\Phi$. A simple and easy choice for $P_0(t)$ variations is a series of pulses (or steps). The impact on sensitivities is illustrated in Figure 1.b that was obtained in the same conditions as for Figure 1.a, except three upstream pressure steps of respectively 25, 40 and 55 bar were applied over an equal period of time Δt=30 mins, t_f remaining unchanged (5400 s). The improvement on $S\Phi$ is obvious and Sk_l/Sb is now varying significantly over the whole experimental duration making possible the simultaneous identification of k_l, b and Φ. In the sequel of this paper, we keep a modulation on $P_0(t)$ under the form of multiple pulses giving the name to the method : the Step-Decay covered by a patent [16].
The robustness of the method is now illustrated using synthetic signals. Four cases were considered for which material characteristics and values of the upstream pressure steps are reported in Table 3, k_l ranging from 10 μD to 10 nD while Φ was varied from 0.01 to 0.1. All other parameters were taken as: D=L=5 cm, P_{1i}=1 bar, $V_0=10^3$ cm^3, V_1=10 cm^3, $\mu=1.8\ 10^{-5}$ Pa.s, m=100 and NP=t_f/dt with dt=1 s (see table caption for t_f values). Synthetic signals $P_0(t)$ and $P_1(t)$ were first generated with a superimposed noise δP (see above) in which dP=0.1 and history matching to identify k_l, b and Φ was then performed on $P_1(t)$, $P_0(t)$ being the excitation. Generated signals in cases 1 and 4 are reported in Figures 2a and 2c respectively. Results of history matching are gathered in Table 3 and examples of residues on $P_1(t)$ in cases 1 and 4 are represented in Figures 2b and 2d. In all cases, the history matching is excellent since errors on all the three identified parameters is less than 0.5%, showing the effectiveness of the method. On this basis, experiments were carried out with the method and are detailed below.

EXPERIMENTAL RESULTS

To validate the new method described above, three core plugs covering wide ranges of permeability and porosity were studied within two different laboratories having their own Step Decay device and own experimental protocol. Lab 1 set-up, represented in Figure 3, is a basic manual test rig while Lab 2 set-up, designed for industrial needs, is made up of four independent and automated measuring cells, all connected to the same gas supply (see Figure 3). Tests were carried out with nitrogen. A typical Step Decay experiment involves the following steps:

- The sample S_a is inserted into a Hassler-sleeve core holder and confined with water at high pressure to reproduce quasi in-situ stress conditions.
- Once the core holder has been introduced in the device, the test starts with the pressurization of the upstream tank V_0, using the regulating valve v_{reg} which controls the gas supply, until reaching the first pulse intensity $(P_{0i})_1$. The valve v_b, upstream from V_0, is closed to isolate the measuring cell from the gas supply system.

- Test starts while opening the valve v_0 downstream from V_0 to allow the pulse emission. This triggers upstream and downstream pressure recordings, $P_0(t)$ and $P_1(t)$.
- Prior to the end of the pulse duration Δt, the next pulse is prepared in the buffer tank V_b. This is achieved by injecting gas through v_{reg} until imposing in V_b a predetermined pressure so that the resulting pressure in V_0+V_b is incremented to a new second pulse initial value $(P_{0i})_2$. The valve v_b is briefly opened at the end of $(\Delta t)_1$ to let the gas expand from V_b to V_0. This step is repeated for each new pulse to generate.
- At the end of the last pulse duration $(\Delta t)_N$, N designating the total number of pulses, both pressure recordings $P_0(t)$ and $P_1(t)$ are stopped and are processed by history matching as described above to estimate k_l, b and Φ. Finally, the leak valves v_{le} and v_1 are opened to enable device depressurization.

Successive operations (tanks pressurization, valves opening and closing, start and stop of pressure recordings) are carried out manually in Lab 1 while Lab 2 equipment allows automatic cycles through the four independent parallel measuring cells once all the experimental parameters N, $(P_{0i})_j$ $(1 \leq j \leq N)$, $(\Delta t)_j$ $(1 \leq j \leq N)$, V_1 and time sampling, dt, have been set into the driver software.

Results obtained independently in Lab 1 and Lab 2 by history matching their own experimental data are reported in Table 4, along with the plug dimensions, D and L, and downstream tank volumes, V_1. It should be emphasized that volumes V_b and V_0 were not measured precisely (just estimated for pressure steps adjustment) since they are not required in the history matching process. Both laboratories confined the three plugs at the same pressure (100 bar), to guarantee a relevant comparison of their respective results. Conversely, for each plug, they modulated their own excitation by selecting separately the number of pulses N as well as the pulse intensities $(P_{0i})_j$ and durations $(\Delta t)_j$ $(1 \leq j \leq N)$.

In Figure 4 are reported the pressure signals $P_0(t)$ and $P_1(t)$ recorded on the three samples, with Lab 1 set-up (Figure 4.a) and Lab 2 set-up (Figure 4.b). All the three plugs were initially at equilibrium at the atmospheric pressure. Moreover, Lab 1 equipment was kept at a temperature of 30 °C in an incubator while Lab 2 experiments were performed in a temperature-regulated room, at 19 °C. Time sampling, dt, of pressure signals was chosen as dt=1 s for Lab 1 and dt=2 s for Lab 2.

Comparison of the results obtained in the two laboratories is assessed by the deviation indicator $D\xi$ (in %) (ξ=k_l, b, or Φ) given by $D\xi = 100\, |\xi_1 - \xi_2| / ((\xi_1 + \xi_2)/2)$. As can be seen from Table 4, the agreement between the results obtained independently is very good taking into account that the two laboratories operated with different protocols. The deviation is around 20% at the most on k_l (it is much less for Plugs 2 and 3) and less than 30% on b on all the samples. Results on porosity are in excellent agreement with a maximum deviation of 6%. This clearly validates the method reproducibility.

CONCLUSION

Optimal conditions to simultaneously identify plug intrinsic permeability, k_l, and Klinkenberg coefficient, b, by a conventional unsteady method are that of the Draw-Down configuration (i.e. an infinite downstream volume) along with a history matching on the upstream pressure decay relying on a complete physical model, making no

simplifying assumptions. Nonetheless, the method does not usually allow the simultaneous determination of k_l, b and porosity Φ of the sample. The reason lies in the sensitivity of the pressure decay to this last parameter that is small and restricted to the very early stage of the experiment whereas pressure disturbances are indeed significant during the period right after the pulse emission. Moreover, some important additional pitfalls of the method were demonstrated. In fact, biases on the porosity (an input parameter in this technique), on the initial value of the pressure pulse (and on V_0), as well as the presence of an upstream dead volume and potential leakage at the sample upstream were shown to have a considerable impact on the estimated values of k_l and b.
A new method was proposed that circumvent all the difficulties highlighted during a Pulse Decay experiment. While the experimental setup remains basically identical to the classical Pulse Decay, it relies on the simultaneous upstream and downstream pressure recordings. The interpretation consists in a history matching based on the complete physical model, carried out on the downstream pressure build up considered as a response to the -measured- upstream pressure excitation. The method is insensitive to all biases mentioned above nor to any upstream disturbance resulting from valve opening, upstream leakage, dead volume, etc. Moreover, the upstream pressure can be time modulated in any way convenient to improve sensitivities so that the three parameters k_l, b and Φ can be precisely identified. This was highlighted on synthetic signals over a wide range of k_l and Φ using an upstream pressure modulation made of a series of pulses, giving the name to the method: the Step-Decay.
The Step Decay was further applied to the characterization of core plugs covering a wide range of porosity/permeability values. Experiments were performed in two independent laboratories having their own Step Decay apparatus and protocols. Results on identified values of k_l, b and Φ are very satisfactory confirming the effectiveness of the method. This method represents a step ahead in the characterization of poorly permeable formation at the core scale and should serve as an advantageous tool to speed up plug characterization while providing a reliable and accurate mean to simultaneously determine permeability, Klinkenberg coefficient and porosity from a single test.

NOMENCLATURE

b	Klinkenberg coefficient	Pa	P	gas pressure	Pa
D	sample diameter	m	$P_0(t)$	pressure at x=0 and t	Pa
DP	error on $P_0(t)$	%	P_{1i}	initial steady-state pressure	Pa
dt	time sampling	s	$P_1(t)$	pressure at x=L and t	Pa
DV	dead volume	m^3	t_f	recording time	s
$D\xi$	deviation on ξ	%	V_b	buffer tank volume	m^3
k	apparent permeability	m^2	V_0	upstream tank volume	m^3
k_l	intrinsic permeability	m^2	V_1	downstream tank volume	m^3
L	sample length	m	δP	Gaussian noise	Pa
m	number of space nodes		Δt	pulse duration	s
NP	number of measuring points		μ	gas dynamic viscosity	Pa.s
N	number of pulses		ϕ	gas pseudo potential $(P+b)^2$	Pa^2
P_{0i}	pulse initial pressure	Pa	Φ	porosity	

REFERENCES

1. Rushing, J., K. Newsham, P. Lasswell, J. Cox, T. Blasingame, "Klinkenberg-Corrected Permeability Measurements in Tight Gas Sands: Steady-State Versus Unsteady-State Techniques", SPE Annual Technical Conference and Exhibition, Houston, Texas, U.S.A., 26-29 September 2004. SPE 89867.

2. Bruce, G., D. Peaceman, H. Hachford, "Calculation of Unsteady-State Gas Flow Through Porous Media", *Petroleum Transactions, AIME*, (1953) **198**, 79-92.

3. Aronofsky J., C. Wallick, P. Reichertz, Method of measuring characteristics of porous materials, **Patent 2867116**, (1959).

4. Brace, W., J. Walsh, W. Frangos, "Permeability of Granite Under High Pressure", *Journal of Geophysical Research*, (1968) **73**, 6, 2225-2236.

5. Jones, S., "A Rapid Accurate Unsteady-State Klinkenberg Permeameter", *SPE Journal*, (1972) **12**, 5, 383-397. SPE 3535.

6. Trimmer, D, "Design Criteria for Laboratory Measurements of Low Permeability Rocks", *Geophysical Research Letters*, (1981) **8**, 9, 973-975.

7. Newberg, M., H. Arastoopour, H., "Analysis of the Flow of Gas Through Low-Permeability Porous Media", *SPE Reservoir Engineering*, (1986) **1**, 6, 647-653. SPE 14705.

8. Kaczmarek, M., "Approximate solutions for non-stationary gas permeability tests", *Transport in Porous Media*, (2008) **75**, 151-165.

9. Hsieh, P., J. Tracy, C. Neuzil, J. Bredehoeft, S. Silliman, "A Transient Laboratory Method for Determining the Hydraulic Properties of 'Tight' Rocks – 1. Theory", *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, (1980) **18**, 3, 245-252.

10. Bourbie, T., "Pulse Decay Permeability: Analytical Solution and Experimental Test", *SPE Journal,* (1982) **22**, 5, 719-721. SPE 9744.

11. Jannot, Y., D. Lasseux, "A new method to measure gas permeabilty of weakly permeable porous media", *Review of Scientific Instruments*, (2012) **83,** 1, 015113.

12. Jannot, Y., D. Lasseux, G. Vizé, G. Hamon, "A Detailed Analysis of Permeability and Klinkenberg Coefficient Estimation From Unsteady-State Pulse-Decay or Draw-Down Experiments", SCA International Symposium, Calgary, Canada, 10-12 September 2007.

13. Jannot, Y., D. Lasseux, L. Delottier, G. Hamon, "A Simultaneous Determination of Permeability and Klinkenberg Coefficient From an Unsteady-State Pulse-Decay Experiment", SCA International Symposium, Abu Dhabi, U.A.E., 29 October-2 November 2008.

14. Lasseux, D., P. Jolly, Y. Jannot, E. Sauger, B. Omnes, "Permeability Measurement of Graphite Compression Packings", *Journal of Pressure Vessel Technology*, (2011) **133**, 4, 041401.

15. Finsterle, S., P. Persoff, "Determining Permeability of Tight Rock Samples Using Inverse Modeling", *Water Resources Research*, (1997) **33**, 8, 1803-1811.

16. Lasseux, D., Y. Jannot, "Measurement of Parameters Linked to the Flow of Fluids in a Porous Material", **Patent WO/2011/089367** (2011).

Table 1. Errors expected on the estimated values of k_l and b due to a bias on Φ.

	Estimated Values		Errors (%)	
	k_l (nD)	b (bar)	$\Delta k_l/k_l$	$\Delta b/b$
Φ+0.2Φ	35	64.8	65.0	395
Φ-0.2Φ	178	0.77	78.4	94.1

Table 2. Errors on the estimated values of k_l and b due to DV and a bias on P_{0i}.

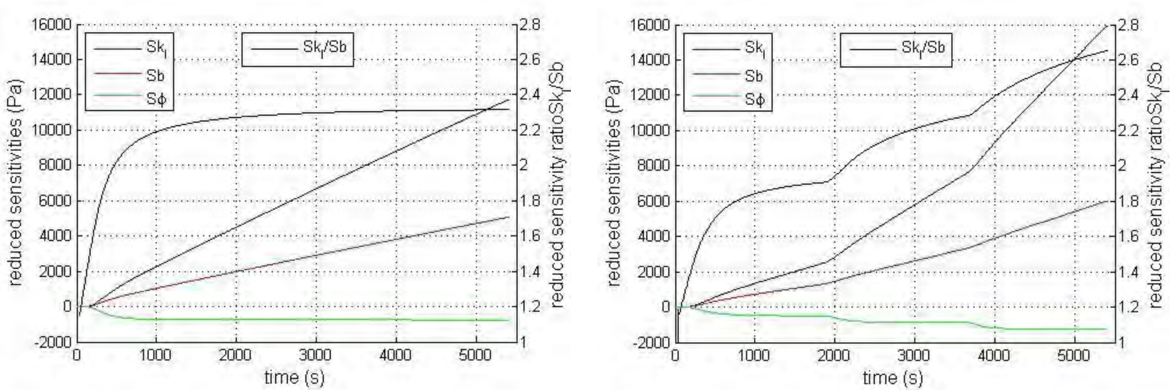
History matching neglecting DV			
Estimated Values		Errors (%)	
k_l (nD)	b (bar)	$\Delta k_l/k_l$	$\Delta b/b$
182	0.45	82	96.5
History matching with a bias on P_{0i}			
Estimated Values		Errors (%)	
k_l (nD)	b (bar)	$\Delta k_l/k_l$	$\Delta b/b$
187	0.19	86.6	98.6

Table 3. History matching results on Step Decay synthetic signals. Values of t_f are: Case 1: 15 min, Case 2: 45 min, Case 3: 90 min, Case 4: 480 min.

		Input values			Estimated values			Errors %		
Case #	N (P_{0i} (bar))	k_l (μD)	b (bar)	Φ	k_l (μD)	b (bar)	Φ	$\Delta k_l/k_l$	$\Delta b/b$	$\Delta\Phi/\Phi$
1	3 (2, 3, 5)	10	2.49	0.1	10.02	2.480	0.10	0.22	0.40	0.21
2	2 (5, 15)	1	5.71	0.05	1.001	5.685	0.05	0.1	0.43	0.29
3	3 (5, 15, 35)	0.1	13.08	0.01	0.1000	13.060	0.01	0.04	0.15	0.23
4	4 (5, 15, 35, 55)	0.01	29.95	0.01	0.01001	29.909	0.01	0.07	0.14	0.09

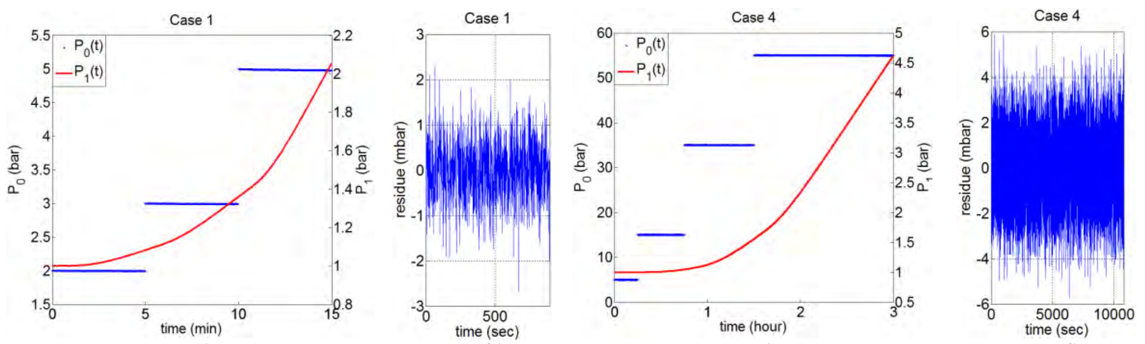
Table 4. Step Decay results from Lab 1 and Lab 2.

	Lab 1 estimates			Lab 2 estimates			Deviations (%)		
Plug #	k_l (μD)	b (bar)	Φ	k_l (μD)	b (bar)	Φ	Dk_l	Db	$D\Phi$
1	0.51	7	0.044	0.41	9.2	0.046	21	27	4
2	14	2.5	0.125	14	3.0	0.128	0	18	2
3	210	0.8	0.104	200	1.0	0.098	5	22	6
Plug 1 – D=4.01 cm, L=6.05 cm, V_1=12.89 cm^3 for Lab 1 / 26.53 cm^3 for Lab 2									
Plug 2 – D=4.01 cm, L=6.05 cm, V_1=12.89 cm^3 for Lab 1 / 26.53 cm^3 for Lab 2									
Plug 3 – D=3.98 cm, L=6.1 cm, V_1=12.89 cm^3 for Lab 1 / 167.98 cm^3 for Lab 2									



a) b)

Figure 1. Evolution of reduced sensitivities Sk_l, Sb and $S\Phi$ and of the ratio Sk_l/Sb. a) One pulse of 35 bar. b) Three pulses of 25, 40 and 55 bar of equal duration Δt=30 min. Test Material (TM).



a) b) c) d)

Figure 2. Pressure decay ($P_0(t)$) in the upstream and build-up ($P_1(t)$) in the downstream reservoirs a) Case 1, c) Case 4. Residue on $P_1(t)$ after history matching b) Case 1, d) Case 4.

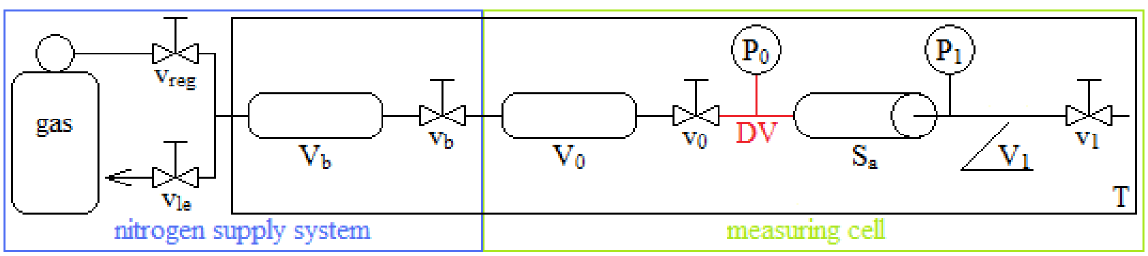


Figure 3. Lab 1 Step Decay apparatus. Note that the measuring cell part of the set-up corresponds to the Pulse-Decay (or Draw-Down) experimental configuration.

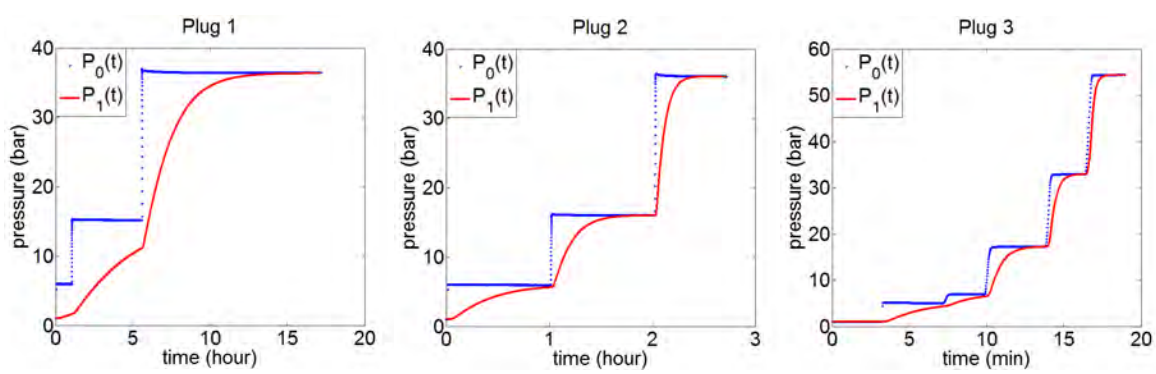


Figure 4.a. Lab 1 Step Decay recordings.

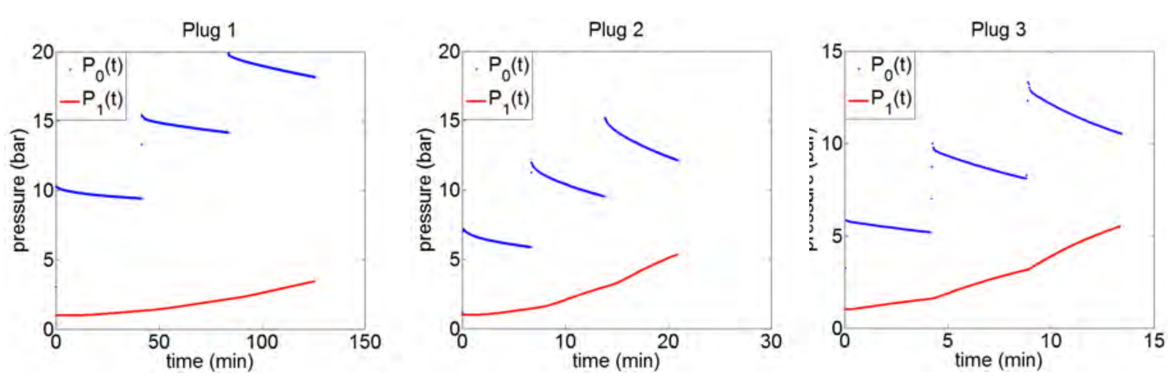


Figure 4.b. Lab 2 Step Decay recordings.