Hydraulic permeability measurements with a syringe pump

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Abstract

We present an experimental procedure for determining the hydraulic permeability of rock samples, from measurements of its hydraulic resistance to the flow of a liquid. This resistance is measured using a programmable syringe pump and a differential pressure sensor. Our results illustrate the dependence of the hydraulic permeability with the residence of the water in rock pore. Hydraulic permeability shows departures up to 23% in comparison to that measured just after saturation.

Introduction

The hydraulic permeability is a physical property that expresses the easiness of the fluid motion trought connected pores and fissures in porous materials, when the liquid is subjected to a pressure gradient. In many geological applications the hydraulic permeability is important to evaluate water and hydrocarbon resources or the assessment of contaminated areas in which the migration of hazardous substances depends on this property.

In laboratory conditions the permeability is measured from controlled percolation tests with a fluid of known viscosity through samples of known shape and size. In general, the rate of percolation must be known as the pressure drop at the sample endings is measured. In most experimental setups requirements of laminar flow and incompressible fluid must be assumed. Departures from such ideal conditions, when gaseous phases are used, tend to overestimate the results of hydraulic permeability in what is called as Klinkenberg effect (TIAB & Donaldson, 2004; Caicedo,1993). This effect is caused by enhanced loss of kinetic energy from viscous forces as the flow regime becomes turbulent (Bruus, 2006). Usual methods to determine rock hydraulic permeability are presented by TIAB & Donaldson (2004).

Here we present apparatus and procedure for measuring the hydraulic permeability of porous cylindrical samples with aqueous (or liquid) phases. Our procedure initially determines the hydraulic resistance of the sample from which the hydraulic permeability can be calculated. A complementary objective of our study is to determine the reliance of the hydraulic permeability with the residence time of the fluid in the porous media. It was done by repeating the measurements weekly, until achieving invariant results. Permeability of shally sandstones is affected by adsorption at clay minerals which changes the effective pore volume. This effect cannot be accounted when a gas phase which then expressess the permeability of the medium under dry conditions, not that found in real geological conditions.

Methodology

Measurements of hydraulic permeability are based on Darcy's law given by

$$k = -\frac{\mu L Q}{A \Delta P} \qquad (1)$$

valid for flow under laminar and saturated conditions(Tiab &Donaldson,2004). In equation (1), k is the hydraulic permeability of the medium (expressed in m^2, or 1 darci=9,869233 x $10^{-13}m^2$), Q is the fluid percolation rate(m^3s^{-1}), ΔP is the pressure drop (Pa) at thesample terminals, μ is the dynamic viscosity of the fluid (Pa.s), A the sample cross section (m^2) and L its length (m).The hydraulic resistance (Bruus, 2006), R_{hyd}, is defined by the ratio

$$R_{hyd} = \frac{\Delta P}{Q} \quad . \qquad (2)$$

From values of hydraulic resistance the hydraulic permeability is obtained as

$$k = \frac{\mu L}{A R_{hyd}} \qquad (3)$$

Experimental Procedure

Equation (3) is the basic relationship on which our experimental approach is based. Since cylyndrical samples are used, parameters L and A easily can be measured directly from the samples. For aqueous solutions viscosity, μ, can be evaluated from standard tables (IUPAC), taking into account its temperature dependence. Our experimental approach then drives attention to accurately determine quantities ΔP and Q that are required to evaluate the hydraulic resistance. Instead of measuring Q, our experimental approach maintain this quantity under constant values by using a precision syringe pump with programable flow steps. Under such conditions the pressure drop at the sample terminals are then measured by coupling a differencial pressure sensor at sealed chambers that encapsulates the sample plug. This experimental setup is outlined in Figure 1.

Constant steps of flow rate were achieved with a precision syringe pump (CHEMIX, Nexus3000) operating at the dual syringe mode, in which two similar syringes are mounted at a single pusher (Figure 2). This mounting allows simultaneous delivery-and-retriving of a same volume of water in each chamber at the sample terminals. As illustrated by the waveform in Figure 3, positive values correspond to the advance of the pusher (by convention toward the right side of the pump when looked from its front panel). The negative values correspond to the return of the pusher to its former position.

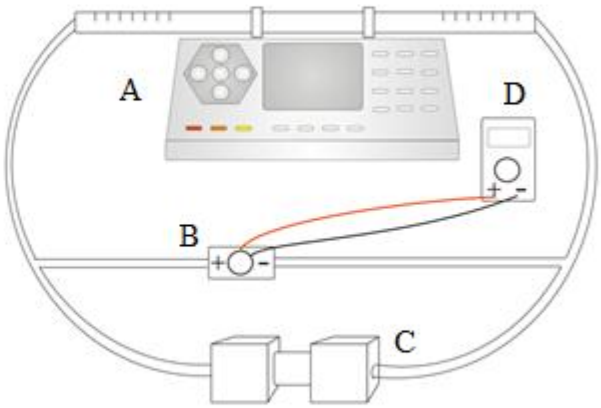

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Figure 1.Experimental setup to measure the hydraulic resistance of a permeable material: syringeump (A), differentialpressuresensor (B), sample holder (C), voltimeter (D).

The driven force at the pusher can reach up to 450lbs (about 2002.5N) and is feed back tuned in order to sustain the prescribed flow rates and delivery intervals defined by the file encoding the waveform.Volumes are delivered in single stages of injection such that each operation stands for 30s. During this interval the pressure drop is measured at regular steps (1s) and then averaged to allow a common statistical support. Volumes delivered by the pump are constrained by the syringe size (10, 20, 60mL) and the pusher speed. The flow rate spanned by the waveform must be compatible with the pressure range covered by the sensor (usually between ±5V) to avoid its saturation. For low permeability materials it implies flow rates as low as a micro litre per second.

Figure 2. Programmable syringe pump (CHEMIX, Nexus 3000), operating at dual injecting-retrieving mode, by coupling two similar syringes onto a common driver (pusher).

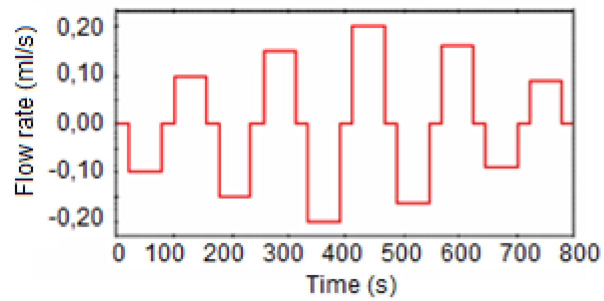

Figure 3. Waveform flow ratedriven by the syringe pump.

Measurements of pressure drop were done with a differential pressure sensor (Termocon, CPC-9800; Figure 4), operating up to 600 mbar. A calibration curve was obtained by applying a water column of variable heights in its positive terminal (higher pressure), the lower terminal kept at the atmosphere. This provides a linear response of type y = ax + b with a = 9.91± 0.02 Vm^{-1}; b=5.11±0.01 V. The output voltage was measured with a digital voltmeter (U1252A, HP) connected to a PC via an optical USB interface. The voltage readings were converted for pressure differential using the calibration curve and them averaged by data pos-processing using scripts in Matlab.

Figure 4.Differential pressuresensor(Termocon, CPC-9800).

The samples were jackted (Figure 5) in order to prevent leakeage and pressure drop as well as hydraulic compliance from deformation of tubes and holders. Air bulbes all along the line were removed by a set three-ways valves.

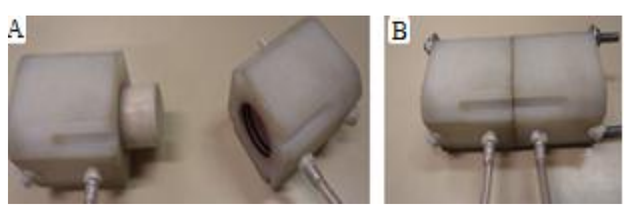

Figure 5. A jacketed plug sample and terminal chambers (A); Holding device when mounted and ready to measurements of the hydraulic resistance (B).

Experimental outputs

Figure6 illustrates the pressure output of a sample (in this case sample 05) when it is subjected to the flow waveform in Figure 3.

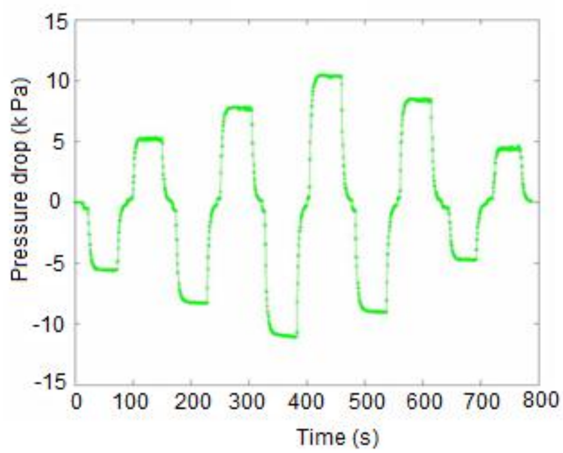

Figure6. Pressure time series at the sample terminals under flow rate of ±100*,* ±150*,* ±200, ±160, ±80 µLs^{-1}.

The evaluation of the hydraulic resistance is illustrated in Figure 7, by pairing corresponding values of flow and pressure drop. Each pair in this plot resulted from averaging corresponding time series for about 15 s using scripts in Matlab. Data fitting and parameters evaluation were done using built in Matlab routines.

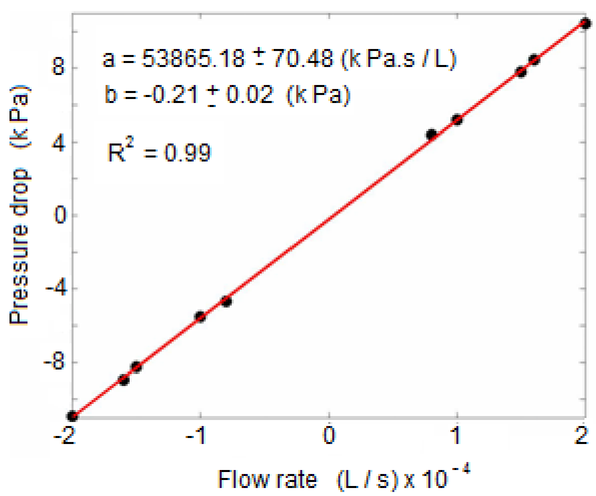

Figure 7. Evaluation of the hydraulic resistance by linear regression of measured flow rate ($10^{-4}Ls^{-1}$) and pressure data (kPa). The hydraulic resistance is estimated as the slope of the fitted straight line.

The experimental procedure illustrade in Figures 6 and 7 was applied to a set testing samples, most of then composed by man-made porous ceramics, some of them with sandstones of paleozoic age from the Paraná Basin.

Measurements were repeated weekly, the results usually estabilizing after a week or two in which the sample was held under saturation. A brief description of the samples and permeability results are presented in Table 1.

Table 1.Hydraulic permeabilityof samples with repetion each week after saturation. Most of the sample are porous ceramic (ABRASIPA) composed by alumina except sample16 composed by silicon carbide. Sample 21 is a sandstone from the Itararé Formation of the Paraná Basin..

	Hydraulic Permeability (D)			
Sample	1st	2nd.	3rd.	Variation (D)
5	1.14	0.95	0.95	0.19
6	0.91	0.69	0.71	0.20
7	2.13	1.82	1.80	0.33
11	6.21	5.43	5.41	0.80
13	1.16	1.13	1.17	0.01
14	2.77	2.47	2.47	0.30
16	0.70	0.91	0.91	0.21
17	2.62	2.78	2.61	0.01
21	0.50	0.58	0.59	0.09

Discussion

Our measurements of hydraulic permeability are comparable to that obtained with other analytical procedures (results not included here). In addition it is effective to highlight the effect of the water residence in the hidraulic permeability. Departures can be as high as 20%, which may be expressive in many applications envolving storage and transport of fluids in porous geological media. On the other hand a simple process to keep samples in batch and then use pumping tests with aqueous solutions to measure hydraulic resistance seem to see effective to obtain more representative values for the hydraulic permeability.

Referências

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