KLINKENBERG PERMEABILITY BY PRESSURE DECAY ON TIGHT ROCKS

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ABSTRACT

Klinkenberg effect becomes more significant in tight rocks. Unsteady-state transient methods have been used in the industry to obtain Klinkenberg permeability. However, higher values are reported compared to conventional steady-state method. In this study we report measurements of Klinkenberg permeability on the same samples using three different methods 1) the steady-state method; 2) the pressure pulse decay method; and 3) the pressure decay (pressure draw-down) method. In addition to the conventional gas permeability method for steady-state measurements with mass flow meter, an accurate capillary tube soap bubble meter was used for samples with microdarcy permeability. The Klinkenberg permeability values are compared with inert oil permeability value. The pressure decay method allows permeability measurements at a wide range of mean pore pressures in a single run. Our results show that accurate Klinkenberg permeability can be obtained in a single run of pressure decay (drawdown) test using Brace's calculation, especially for tight rock samples in the permeability range of milidarcy to microdarcy.

INTRODUCTION

Gas permeability depends not only on the rock flow properties and types of probe gas, but also on the mean pore pressure at which it is measured. Gas permeability is higher than its intrinsic permeability due to the effect of "gas slippage" [1]. Hence the Klinkenberg permeability, which is independent of the type of probe gas and measuring pressures, as opposed to the gas permeability, is more commonly used in core analysis and it can be taken as inert liquid permeability.

Klinkenberg permeability can be obtained either by steady-state or unsteady-state method. Using the steady-state method, the permeability is normally obtained by measuring several gas permeability values at different mean pore pressures. The Klinkenberg permeability can then be calculated. Alternatively, unsteady-state pressure decay (draw-down) method can be used to obtain the Klinkenberg permeability by a single run [2,3]. However, as it has been reported [4,5,6], unsteady-state method gives higher Klinkenberg permeability values compared to steady-state ones. In our routine measurements, we also consistently measure much higher Klinkenberg permeability using industrial standard unsteady-state permeameter and data processing method [2], compared to those from steady-state method under similar conditions. With the increasing activities of exploration and P&D in tight gas in the permeability range of mili-micro darcy, fast and accurate methods are apparently more important than ever before.

The aim of this study is to investigate the unsteady-state method, by comparing it to the steady-state method for Klinkenberg permeability in terms of experimental setup, data processing methods, gas types under well-controlled conditions.

Our results show that the unsteady-state pressure decay method can give the same Klinkenberg permeability as the steady-state method for samples ranging from millidarcies to microdarcies, when Brace's method [7,8] is used for the calculation.

SAMPLES, METHODS AND EXPERIMENTAL

Four samples with permeabilities ranging from millidarcies to microdarcies were selected for the study. Nitrogen and Helium gases were used in unsteady-state measurements. In the steady-state measurements, only Nitrogen gas was used. The Klinkenberg permeability values obtained in the steady-state and unsteady-state measurements were compared. Oil permeability was compared as a reference to the Klinkenberg permeability on the same sample. All experiments were performed at the same effective confining pressure of 500 psi.

Klinkenberg permeability by steady-state method (SS)

For the two samples with a relative higher permeability, the steady-state gas permeability was measured using a permeameter equipped with a mass flow meter with Nitrogen as the probe gas. The volumetric gas flow rate was converted to ambient conditions of temperature (20℃) and 1 atm pressure. Gas permeability was calculated using Darcy's law. For each sample several gas permeability values were obtained at various mean pore pressures. The mean gas pressures were selected from a wide pressure range to allow for an accurate regression [9]. The gas permeability values were plotted against inverse mean gas pore pressures. The fitting line was extrapolated to zero (infinite pore pressure) to obtain Klinkenberg permeability. The slope can be used to calculate the gas slippage factor *b*.

$$K_g = k_L(1 + b/P_m) \quad (1)$$

For sample S4 with low permeability, the steady-state permeability was measured using an accurate micropipette as a gas bubble flowmeter.

Klinkenberg permeability by pressure pulse decay (PPD)

Detailed information about the pulse decay apparatus developed by PanTerra and University of Utrecht was published previously [8]. The transient pressure pulse decay setup consists of an upstream and downstream reservoir. A small pressure pulse is applied in the upstream reservoir and the differential pressure allows gas flow from the upstream reservoir, through the sample and to the downstream reservoir. The pressure changes across the sample and in the two reservoirs are recorded as a function of time.

The apparent gas permeability was then calculated based on the method originally proposed by Brace et al. [7] although many other calculation methods were proposed [10,11,12]. When a pressure pulse ΔP_0 is applied, the differential pressure $\Delta P(t)$ decays exponentially as a function of time, *t*:

$$\Delta P(t) = 2\,\Delta P_0\, V_2/(V_1 + V_2)\, e^{-mt} \quad (2)$$

Where, V_1 andV_2 are the upstream and downstream reservoir volumes and t is testing time. m is a decay time constant. Plotting the decay curve in terms of $ln[\Delta P(t)/\Delta P_0]$ vs. time t yields a straight line having a slope m. The permeability k can be determined by:

$$k = m\,\mu\beta(L/A) \times [V_1\, V_2/(V_1 + V_2)] \quad (3)$$

where
L - length of the sample,
A - cross-sectional area of the sample,
μ- Nitrogen viscosity at room temperature and mean pore pressure,
β -Nitrogen compressibility.

Four gas permeability measurements using Nitrogen (N2) were performed for sample S3 at various mean pore pressures. The Klinkenberg permeability was then calculated the same way as four-point Klinkenberg permeability by steady-state method. For sample S4, two gas permeabilities were measured at high mean pore pressures.

Klinkenberg permeability by pressure decay (draw-down) method (PD)
The pressure decay (PD) or the draw-down method can be considered as a special case of pressure pulse decay as described above with an infinitely V2 volume and a fixed down-stream pressure of 1atm.

Two permeameters were used for the pressure decay gas permeability measurements. The first one is the PanTerra in-house pressure pulse decay permeameter with down-stream reservoir open to atmosphere. Nitrogen gas was used for this apparatus. A series Nitrogen gas permeability values were calculated using the Brace method as described above at each mean pore pressure step.

The second permeameter was from an industry provider. This is a combined Helium permeameter and Helium porosimeter. The automated permeameter provides Klinkenberg permeability and gas slippage factor b for Helium. The calculation is based on the method proposed by Jones [2][3]. The Helium gas permeability values were reconstructed based on the Klinkenberg permeability, the Helium slippage factor b and the pressure decay data.

We also re-calculated the Helium gas permeability values based on the pressure decay data using the Brace method and using the equipment parameter such as V1 volume and Helium gas properties. Klinkenberg permeabilities for samples of S1, S2 and S3 were re-calculated based on the re-calculated Helium gas permeability.

Oil permeability
For the two samples of S1 and S2, the oil permeability (Kerosene lab oil) was measured after the gas permeability. For each sample four flow rates were applied in the measurements. The two samples were cleaned after oil permeability measurement and Klinkenberg permeability re-measured by the steady-state method. The same value of Klinkenberg permeability was obtained as the original one before oil permeability measurement. The oil permeability values are shown in Figure 1 and Figure 2 as inverse

of mean gas pore pressure of zero to compare with their gas permeability and Klinkenberg permeability. Please note that these mean pore pressures are only for comparison with gas and Klinkenberg permeability and not the true mean pore pressures in oil permeability tests.

DISCUSSION

For sample S1 (cf. Figure 1), the Klinkenberg permeability derived from the Brace method matches the Klinkenberg permeability from steady state measurement by using Nitrogen. The Klinkenberg permeability is close to the oil permeability. The Klinkenberg permeability by Jones method gives a value 50% higher.

For sample S2 (cf. Figure 2), four Klinkenberg permeability were obtained. Among them, three are close to the oil permeability given the experimental error. However, the Klinkenberg permeability calculated based on the Jones' method is two times higher.

For sample S3 (cf. Figure 3), the pressure pulse decay method and pressure decay (draw-down method) tested using the same apparatus and same probe gas of Nitrogen give the same results of Klinkenberg permeability considering the experimental error. The Klinkenberg permeability by a different apparatus, and different probe gas of Helium also give the same value when data is reprocessed using the Brace method. The Klinkenberg permeability by the Jones' calculation [2] gives a value two times higher compared to the rests.

For sample S4 (cf. Figure 4), the gas permeability measured by the steady-state method gives the same results as measured by single pressure decay run when compared at the same mean pore pressures. The pressure decay (draw-down) method gives comparable results with pressure pulse decay method when extrapolated to the same mean pore pressure. All measurements for sample S4 give the same single Klinkenberg permeability.

It is evident that the Klinkenberg permeability based on the pressure decay data and Jones method give a value too high. However, the same data when processed with Braces' method [8] give much close values to those obtained from steady- state method. It seems that Jones method masked the effect of "*b*" on the individual sample. By applying brace method while using the pressure decay setup, a more accurate Klinkenberg permeability can be obtained, furthermore a characterized '*b*" value can be obtained which has the potential to be used for pore characterization in tight rocks. The number and type of samples tested in this study are limited. More works are planned to continue the studies in terms of enlarging the database and refining the algorithm of Brace method et al.[7].

CONCLUSIONS

Unsteady-state pressure decay (drawdown) is a quick method to obtain accurate Klinkenberg permeability for tight rock in the permeability range of millidarcy to microdarcy. Experimental results show that the unsteady-state method gives the same Klinkenberg permeability results as steady-state method. More work needs to be done on different samples in a wider permeability range.

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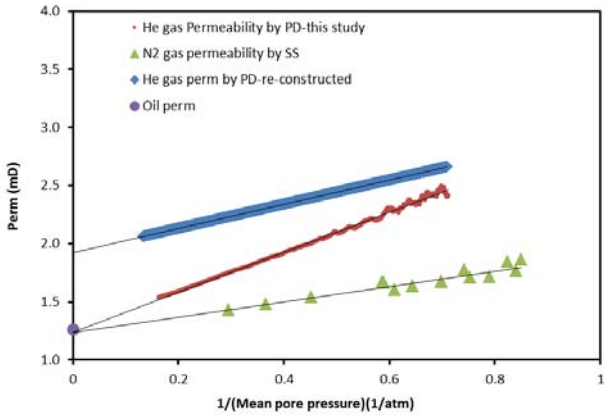

Figure 1. Sample S1: Klinkenberg permeability measured by 1) unsteady-state pressure decay (draw-down) using Helium; 2)Klinkenberg permeability measured by steady-state method using N2 gas (green triangle); 3)permeability of lab oil (purple dot).

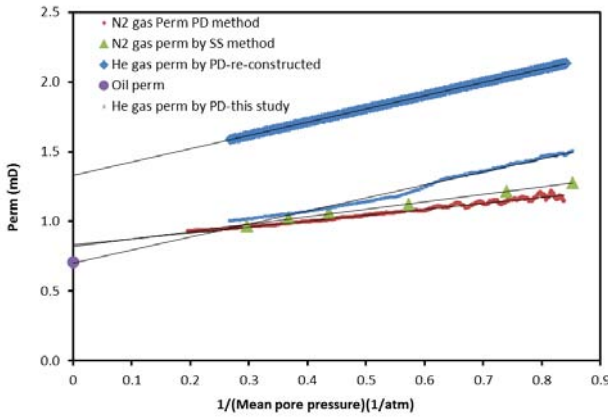

Figure 2. Sample S2: Klinkenberg permeability measured by 1) unsteady-state pressure decay (drawdown) using Nitrogen; 2)Klinkenberg permeability measured by steady-state method using N2 gas)(green triangle; 3)permeability of lab oil (dot). 4)unsteady-state pressure decay for Helium calculated by Jones method; 5) unsteady-state pressure decay (draw-down) using Helium calculated by Brace's method.

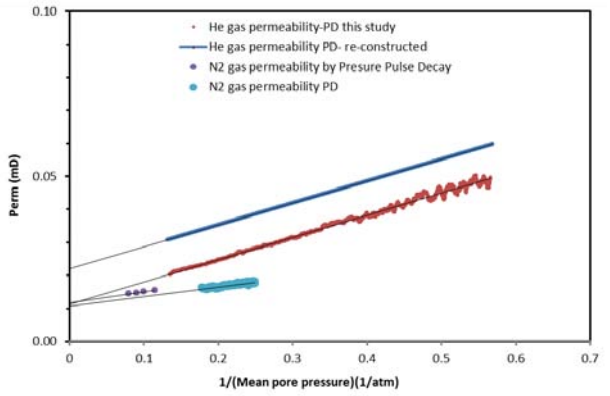

Figure 3. Sample S3: Klinkenberg permeability by 1) unsteady-state pressure decay (draw-down) using Helium; 2) unsteady-state pressure decay (draw-down) using (N2) Nitrogen; 3)Klinkenberg permeability by four pressure pulse decay measurements using N2 gas; 4)unsteady- state pressure decay for Helium calculated by Jones method.

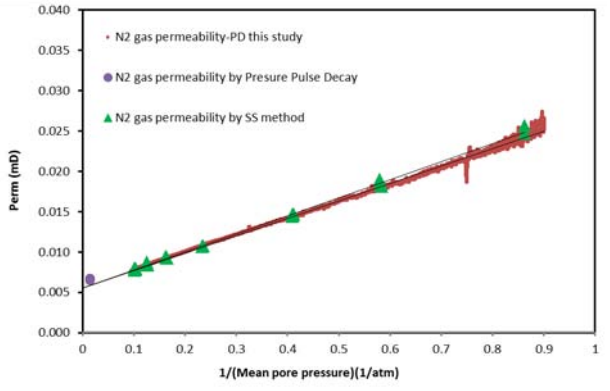

Figure 4. Sample S4: Gas permeability by 1) unsteady-state pressure decay (draw-down) using (N2) Nitrogen; 2) pressure pulse decay measurements using N2 gas; 3) gas permeability measured by steady-state method.