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Full Length Article

# Optimized pressure pulse-decay method for laboratory estimation of gas permeability of sorptive reservoirs: Part 2 - Experimental study

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ABSTRACT

Since pressure measurements can be made more conveniently and accurately compared to fluid flowrate, the pressure transient technique is considered an advanced method for laboratory permeability measurement of unconventional gas reservoir rocks, specifically, gas shales, tight gas sand, and highly-stressed coalbed methane (CBM) reservoirs. However, two major factors, compressive storage and sorption effect, can lead to enormous error when testing sorptive rocks using the pulse-decay method (PDM). In order to overcome these, an optimized PDM experimental design of the transient technique for permeability testing of unconventional gas reservoir rocks was introduced in Part 1 of this two-part series. A modified mathematical model, describing one-dimensional fluid flow in porous media and best representing the optimized PDM design, was then presented to numerically investigate the fluid flow behavior and theoretically verify the applicability of Brace et al.'s solution in permeability calculation of sorptive rocks.

To experimentally illustrate and verify the applicability of the optimized experimental design under best replicated *in situ* stress/strain conditions, a core of coal from San Juan basin was tested under triaxial stress. The experimental results showed that accurate and time-saving measurement can be achieved by choosing appropriate fluid reservoir volumes. Based on characterization of the pressure pulse decay plots, it was concluded that the effect of compressive storage on pressure variation in the up-/down-stream reservoirs and permeability calculation can be avoided when applying the optimized PDM.

$CO_2$ was used as the test fluid to investigate the effect of sorption on pressure variation due to its higher affinity towards coal than methane. The experimental results showed that sorption effect was eliminated, leading to accurate permeability values. A similar permeability trend with pressure drawdown, as previously measured for San Juan basin coal, was established. Also, comparison of the measured pressure decay plots and those obtained from computer simulation exhibited perfect matches, indicating that Brace et al.'s solution can be used for permeability estimation of sorptive rocks by adopting the optimized transient technique.



## 1. Introduction

For laboratory testing of low permeability rocks, the pressure pulse-decay method (PDM) is more practical and applicable than the steady-state flow method. As cited by Lin [1], although permeabilities from $10^4$ to $10^{10}$ nD can be determined directly from measurements of fluid flow and pressure drops across rock samples, permeabilities from 1 to $10^5$ nD should be estimated by the use of the transient technique. Brace et al. [2] also claimed that the transient method is more convenient when measuring permeability of less than about $1 \times 10^{-14}$ cm$^2$ (1 μD). However, some critical issues exist in the currently-used PDM solutions, such as, compressive storage and sorption effect. As stated in Part 1 of this two-part series, these can result in erroneous results in permeability calculation. Although permeability of a sample can be obtained graphically from a pulse test, based on either theoretical analyses [3] or numerical approaches [4,5], the associated procedures are relatively complicated and their accuracy is limited. To date, most investigators still prefer the simplified solution developed by Brace et al. [2] to interpret their experimental results, thereby obtaining only an unsatisfactory estimate of rock permeability.

However, Brace et al.'s solution is best suited for testing samples with negligible compressive storage since the validity of using the solution to calculate rock permeability is affected directly, and constrained, by the effect of compressive storage. Additionally,

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sorption effect can play a major role, resulting in considerable errors in the calculated permeability when testing sorptive rocks, particularly, those exhibiting strong adsorption characteristics when the conventional PDM is used. In Part 1, a modified mathematical model, best representing one-dimensional fluid flow in porous media and describing the decay or enhancement of dual pressure pulses in the optimized transient technique, was presented to numerically evaluate the transient variations of pressure in time and space domain. The effects of compressive storage and adsorption when testing sorptive rocks on the pressures responses, and the importance of considering these two factors during a pulse test, were demonstrated theoretically and numerically. Also, optimization of the dimensions of the up-/down-stream reservoirs and determination of the sizes of the pressure pulses applied to the test sample were illustrated.

Although the applicability of the optimized PDM was theoretically analyzed and numerically verified in detail in Part 1, the efficiency and applicability of the technique requires demonstration through its direct application to experimental work designed to establish the permeability trend under best replicated *in situ* conditions. In this study, $CO_2$ was used as the test fluid to profile and characterize the pulse decay plots due to its higher affinity towards coal than methane, and then establish the pressure-dependent-permeability trend for highly-stressed CBM reservoirs. This paper also verifies the Brace et al.'s solution by comparing the lab data and computer simulated results obtained from the optimized mathematical model proposed in Part 1. The experimental work demonstrates that the optimized technique can be used for permeability tests of sorptive rocks without the need to carry out additional experimental work required to measure rock porosities and sorption isotherms.

## 2. Previous experimental studies

In Part 1 of this study, different types of analytical solutions for describing the pressure pulse decay characteristics were presented, and the commonly-used PDM solutions proposed for calculating permeability were reviewed. To avoid duplication, theoretical development and previous experimental work conducted using the PDM is introduced here only briefly.

Due to the difficulty in laboratory determination of permeability by conventional techniques using measurements of fluid flowrate through a sample under a constant pressure gradient, Brace et al. [2] was the first to carry out permeability experiments using a transient method for permeability measurement of crystalline metamorphic and igneous rocks by monitoring the decay of a small step change of pressure imposed at one end of a sample. The pressure decay characteristics, when combined with the dimensions of the test sample and fluid reservoirs, along with the physical properties of the test fluid, yielded permeability of a thin Westerly granite sample (L = 1.61 cm), held under hydrostatic pressures up to 444 MPa. Lin [4] conducted an investigation on the difference in permeability estimated by Brace et al.'s method and a numerical method, and pointed out that the permeability value determined by Brace et al.'s method was larger than that determined by the numerical method, depending on several factors, such as, rock properties, sample size and reservoir volumes. To investigate the argon gas permeabilities of seven rock salt samples as a function of hydrostatic compression and time, a series of experiments were conducted by Sutherland and Cave [6] using the conventional transient technique as proposed by Brace et al. [2]. However, in their study, the downstream reservoir volume was two-orders of magnitude smaller than the upstream reservoir. There were two issues that need to be addressed about their work. First, the objective of this design was not elucidated by the authors. Second, their study ignored the effect of compressive storage of the test sample and fluid reservoir volumes on permeability estimation, as discussed in Part 1.

Hsieh et al. [7] proposed a mathematical model in terms of an initial-boundary value problem to describe fluid flow in a transient pulse test, and a general analytical solution was then derived to describe the variation in hydraulic head of the upstream and downstream reservoirs with respect to time. This solution was graphically illustrated by plots of dimensionless hydraulic head for several cases of interest. In a subsequent study, Neuzil et al. [3] presented a graphical method for analyzing data from tests using two shale samples to obtain the hydraulic conductivity and specific storage of the sample. It should be pointed out that this graphic method is time-consuming and, hence, less practical in permeability estimation. Based on Hsieh et al.'s analytical solution, taking full advantage of the symmetry of the setup for the conventional transient technique, Dicker and Smits [8] developed an improved pressure-pulse decay method to measure permeability of tight rock samples, enabling fast and accurate permeability

**Table 1**
Chronological summary of the pressure transient technique (after Kamath et al. [11]).

| Authors | $V_p/V_u$ | $V_p/V_d$ | Comments |
|---|---|---|---|
| Brace et al. [2] | ≈0 | ≈0 | Single exponential pressure decay valid over most of time domain |
| Jones [12] | ≈0 | ≈0 | |
| Forster and Gale [13] | ≈0 | ≈0 | Brace et al.'s exponential solution |
| Yamada and Jones [14] | ≈0 | ≈0 | Late-time exponential solution predicted to be valid using numerical method |
| Hsieh et al. [7] | | | A general, analytical solution was derived; compressibility not a function of fluid pressure |
| Neuzil et al. [3] | 1.5 | ≈0 | |
| | 0.2 | 0.8 | |
| Bourbie and Walls [15] | ≈0 | ? | Early-time (erfc × exp) solution solved iteratively |
| Freeman and Bush [16] | ≈0 | 0.2–1 | |
| Chen and Stagg [17] | ≈0 | 0.53 | Late-time exponential solution |
| Amaefule et al. [18] | 0.25 | ≈0 | Late-time exponential solution |
| Walder and Nur [19] | ≈0 | ? | Early-time (erfc × exp) solution solved iteratively |
| Maini and Okazawa [20] | 0.05–0.19 | ≈0 | |
| Bernabe [21] | ≈0 | ≈0 | Brace et al.'s exponential solution |
| Haskett et al. [22] | 0.10 | 2 | Porosity and permeability from history matching completion solution |
| Kwan et al. [23] | 0.08–0.90 | ≈0 | Late-time exponential solution |
| Holder et al. [24] | ? | ≈0 | Numerical solution forward and reverse pulses |
| Dicker and Smits [8] | | | Applied two equal-volume fluid reservoirs |
| Ruth and Kenny [25] | ≈0 | ≈0 | |
| Kamath et al. [11] | | | Interpreted characterization of core-scale heterogeneities |
| Jones [9] | | | Simplified Dicker and Smits (1988)'s analytical solution |
| Cui et al. [10] | | | Incorporated Langmuir model into permeability estimation |

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