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Laboratory measurement of low permeability unconventional gas reservoir rocks: A review of experimental methods

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ABSTRACT

Unconventional natural gas has become an important source of energy. However, the development of such resources has been challenging as these reservoirs are characterised by low to ultra-low permeabilities. The low permeability does not only present a challenge for commercial gas production, but also for experimental measurements of rock samples. Methods to determine permeability of low permeability rock cores and crushed rock samples directly can be divided into two categories: steady state and unsteady state. Unsteady state methods include the pulse decay, oscillating pressure, and GRI method (pressure fall-off method). In this review we describe and compare each method in detail and discuss the challenges specific to measuring low permeability rocks. A brief overview of alternative permeability measurements is also provided (e.g. indirect measurements, canister desorption test).

The review highlights each method's advantages and disadvantages. The steady state method is easy to apply, due to its simple experimental set-up and its straightforward solution using Darcy's law. However, as permeability decreases, flow rate measurements become less accurate. Unsteady state experiments measure pressure and temperature, which can typically be determined more accurately. Furthermore, the set-up of unsteady state experiments can be adapted to increase sensitivity, thus improving measurement accuracy or speed. On the downside, unsteady state experiments are typically more affected by leaks than steady state experiments.

The review indicates that steady state and unsteady state methods do not always yield the same results, and that the GRI method measures a different type of permeability to the other experimental methods. The permeating fluid can also significantly affect measurements in very low permeability rocks. Additionally, the experimental measurement of low permeability gas reservoir rocks faces several practical challenges: a lack of universal measuring standards for low and ultra-low permeability media affects comparability between results; different laboratories use different methodolgies for sample preparation; and various analytical solutions have been presented to interpret the experimental data, most of which are based on the validity of Darcy's law and the Klinkenberg effect.

The suitability of an experimental method depends on permeability, porosity and adsorption capacity of the rock, and the limitations of the underlying assumptions of the solution. A thorough understanding of the applied experimental and analytical technique, and knowledge of the sample's preparation are necessary to accurately interpret and use any results.

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1. Introduction

Unconventional natural gas, which includes shale gas, coalbed methane and gas from tight sandstones, has become an important source of energy. Developing such natural gas resources requires a sound understanding of reservoir properties, of which permeability is typically considered the critical parameter for commercial gas production (e.g. Boyer et al., 2006; Palmer, 2010; Pan and Connell, 2015). Testing permeability in the field may be the most reliable means of obtaining representative permeability measurements. However, gas permeability is difficult to fully characterise in the field, because it is a function of pressure and effective stress and thus changes with changing reservoir conditions. It is also affected by gas adsorption on organic-rich rocks, such as coal (Palmer and Mansoori, 1998) and shale (Wasaki and Akkutlu, 2015).

To develop permeability models for gas production calculations, we need to understand how permeability responds to these factors. Laboratory characterisation allows us to specify and control conditions and is thus a useful tool to obtain such knowledge. Experiments can be carried out under a range of conditions, simulating different stages during gas production or gas injection. A comprehensive experimental program requires permeability measurements as a function of gas pressure, effective stress, adsorption amount and temperature. However, laboratory measurements on unconventional gas reservoir rocks are challenging due to their low to ultra-low permeabilities (with ultra-low being defined as 0.001 millidarcy (mD) and below). Typically, coal permeability ranges from microdarcy (μD) to a few hundred millidarcy, while tight sandstone reservoirs have permeabilities of less than 0.1 mD (see Fig. 1). Shale permeability ranges from nanodarcy (nD) to a few microdarcy, although shale samples with permeabilities of less than 1 nD have also been recovered and experimentally analysed (Chalmers et al., 2012; Amann-Hildenbrand et al., 2013; Ghanizadeh et al., 2014a). These extremely low permeabilities are typically encountered in the direction perpendicular to bedding.

For low to ultra-low permeability reservoir rocks, permeability measurements are likely to be time consuming, making the choice of the experimental method important. Gensterblum et al. (2015) presented an overview of the permeability measurement ranges of different experimental techniques. However, it is difficult to specify an applicable range for each technique, as this strongly depends on the individual experimental set-up and the sample itself. An overview of experimental low and ultra-low permeability measurements and the methods used to obtain them is given in Tables 1–7, which indicate that steady state and unsteady state methods (pulse decay, oscillating pressure and GRI method) can all measure permeabilities in the nanodarcy range, if the experiment is designed appropriately. This is not to say that all methods are equally suitable to measure low permeability rocks, which is something we assess as part of this review. Fig. 1 presents an