RESERVOIR PROPERTIES OF CONVENTIONAL ROCK: ROUTINE MEASUREMENTS ON MINI-PLUGS

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ABSTRACT

While analyzing heterogeneous reservoir rocks it is extremely important to measure reservoir and other properties on the same core plug (Fig. 1). Conventional techniques for core analysis were designed for core plugs with diameter 30 mm and more. From the other side, routine (RCA) and special (SCAL) core analysis on miniplug are getting more and more essential with growth of interest to numerical pore-scale simulation, which require utilization of miniplugs for getting high resolution X-Ray microCT images rock's porous structure [1]. The physical analysis of the miniplugs is the most straightforward way to validate and verify the numerical results. We adapted an existing RCA methodology and equipment for measurements on small size cores, which are applicable for micro-CT. Thus, the main goal of this study was development and validation of an approach for laboratory core analysis on mini-plugs that are core plugs with diameter 5–10 mm.

For the analysis of a mini-plug we have modified conventional techniques and equipment for reservoir properties measurements. To estimate quality and applicability of such approach a little upscaling study had been performed. During the upscaling exercise we tested our approach on mini-plugs and compared results of measurements on conventional core plugs and on mini-plugs which were extracted from the same piece of rock.

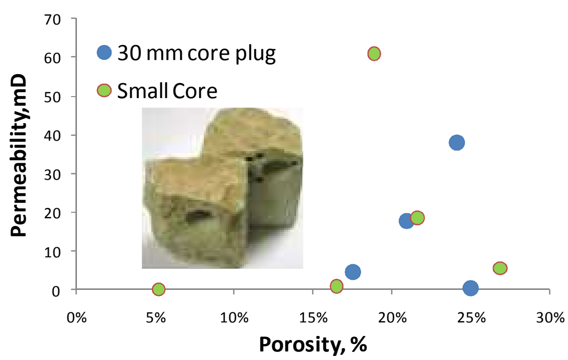

Fig. 1. Dependence of permeability on porosity for the same piece of rock (limestone) as an example of heterogeneity for porosity and permeability.

QUALITY OF POROSITY AND PERMEABILITY MEASUREMENTS

Before any modification or improvement of an existing laboratory method it is crucial to understand quality of the measurements and estimate its precision and accuracy. It is well known that error for porosity measurements are commonly accepted to be less than 0.001 p.u. and 5% for gas permeability measurements [2]. To check it we performed a round robin test that included numerous measurements on a set of artificial core plugs of conventional size (Ø30 mm) made of ceramic. The set of 8 ceramic cylindrical plugs 30×30 mm with relatively high porosity (14–30%) and wide permeability range (0.6–1350 mD) participated in the test. Eight core laboratories with more than 20 porosimeters and permeameters were involved in the test. Permeability was measured by gas with both steady-state and pressure falloff methods. Porosity was measured by gas and water.

The round robin test in spite of using equipment of the well-known manufacturers and in good technical conditions demonstrated excellent precision and bad accuracy: repeatability was better than ±0.05% for the most instruments but systematic difference was up to ±0.4% (at porosity values 14–30%) even between porosity values measured by the same type and hardware version of porosimeters. As for permeability measurements, we also observed significant discrepancy 20% and more for data obtained with different permeameters. In contrast to porosity measurements where accuracy did not depend on porosity value, permeability measurements turned out to be most problematic for low (below 1 mD) and high (above 500 mD) permeable cores. By the way, even for good permeability range (1–500 mD) we observed poor accuracy ±2–10% at high precision (repeatability better than ±1%) for results of different permeameters.

CORE PREPARATION AND EXPERIMENTAL PROCEDURE

In the present work we proposed an approach for mini-plug characterization using slightly modified conventional equipment. The mini-plug we study is a cylinder Ø8 × 8 mm. This size was chosen because we can get high-resolution 3D image with X-ray micro CT on the one hand and prepare the same mini-plug for RCA and SCAL on the other hand. Plugging, cutting and trimming were performed using a standard equipment. Prior to the tests, all samples were cleaned using distillation extraction method in a Soxhlet extractor. After cleaning, all the samples were dried in a vacuum oven at temperature 60 to 90 °C. The temperature for mini-plug drying was the same as recommended for conventional core analysis [2].

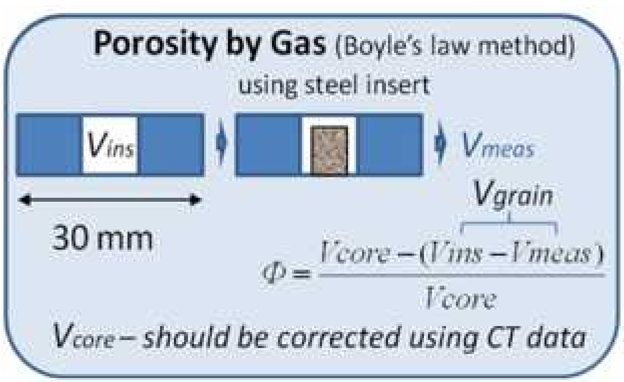

Fig. 2. Workflow for porosity measurements

Mini-plug porosity determined from measurement of core matrix volume by gas using Boyle's law with conventional equipment for RCA. To adopt the system for core mini-plugs we manufactured a set of special inserts: metal disks with OD 30 mm (corresponding to inner size of coreholder) and an Ø8.2 mm hole in the center (slightly larger than mini-plug diameter). Height of the inserts varies from 8 to 55 mm (for different length of core mini-plugs).

Porosity measurements were performed in 3 stages (Fig. 2): (1) determination of volume of the insert; (2) measurement of gas volume of the insert with a mini-plug inside and (3) measurement of mini-plug total volume using micro-CT image. Mini-plug porosity was calculated from the measurements using the simple formula (Fig. 2).

Gas permeability of small-size cores can be measured by both steady-state and pressure falloff methods. We use the conventional permeameter for pressure falloff methods and its coreholder for steady-state method. To properly use a permeameter designed for the conventional core plug analysis we manufactured a special insert made with rubber. Several significant improvements should be made for mini-plug characterization by conventional porosimeter/permeameter: pressure gauges should be replaced with high precision one and should be calibrated; volume of all tanks should be measured with high accuracy and precision; no leakage is allowed; good temperature stabilization of the whole setup should be achieved.

UPSCALING TEST – VERIFICATION OF PROPOSED APPROACH

Proposed approach was tested on collection of 11 core plugs drilled out of relatively homogeneous rocks including such as Berea, Bentheimer, Parker sandstones, Austin chalk and other terrigenous and carbonate rocks. Porosity range for the sample collection was 5–29% and permeability range is within 1–500 mD. Before measurements the core plugs Ø30 mm were cleaned and dried. Then porosity and permeability were measured at least 4 times. After quality control we drilled a mini-plug out of each core plug. Porosity and permeability of mini-plugs were measured after drying. Results of the upscaling test are presented in Fig. 3 and 4. Measurements of porosity and permeability of both plugs and mini-plugs were performed on the same equipment so accuracy of measurements (pore volume, flow rate, pressure drop etc.) are the same for both Ø30 mm cores and mini-plugs.

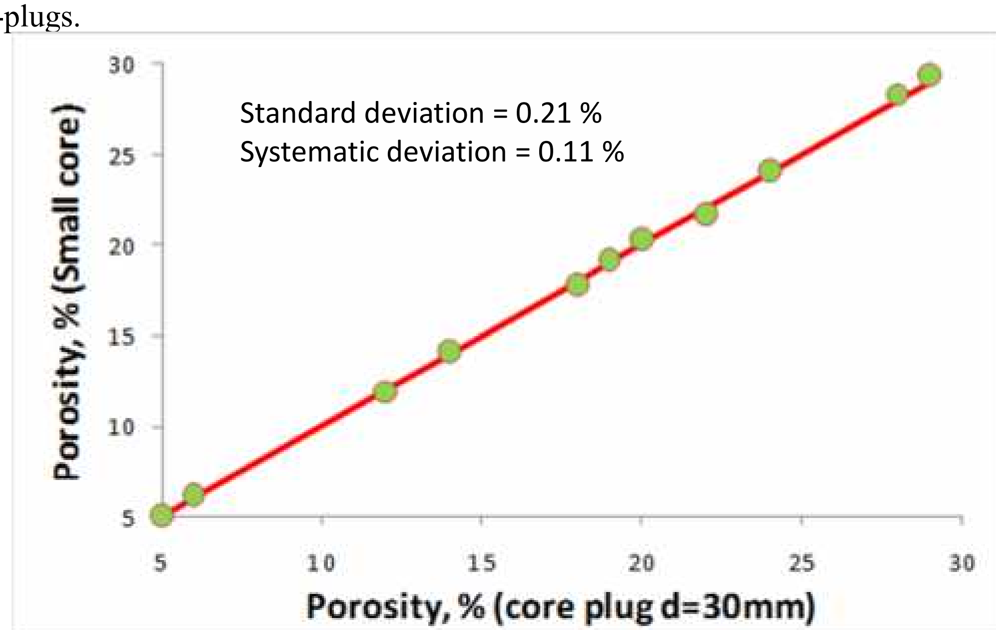

Fig. 3. Comparison of porosity data obtained on mini-plugs and Ø30 mm core plugs.

Porosity values measured on mini-plugs are close to data obtained on 30 mm core plugs (fig. 3). Each porosity measurement on a mini-plug included at least 4 measurements to improve precision. Results shown in figure 3 demonstrate that porosity values measured on mini-plugs for the most pairs of cores are slightly higher with respect to standard ones: systematic deviation is 0.11%. The deviation is likely caused by presence of small vugs or caves on the external surface of the mini-plugs. Therefore, to improve quality of porosity measurements it would be better to determinate sample volume using micro-CT or at least to use immersion weighting if mini-plug is saturated otherwise volume of vugs or misalignment of edges would be included in porosity.

Results of permeability are not so sensitive to quality of sample length and cross-sectional area measurements like porosity measurements. We successfully tested both steady-state and pressure falloff methods on mini-plugs. Each permeability value determined by both methods includes at least 3 independent measurements. Comparison of permeability measured on mini-plugs Ø8 mm and Ø30mm core plugs is shown in fig. 4. We have not found any systematic deviation for both steady-state and pressure falloff methods. Moreover, neither Klinkenberg corrected permeability nor inertial coefficient (β-coefficient) depended on core plug size.

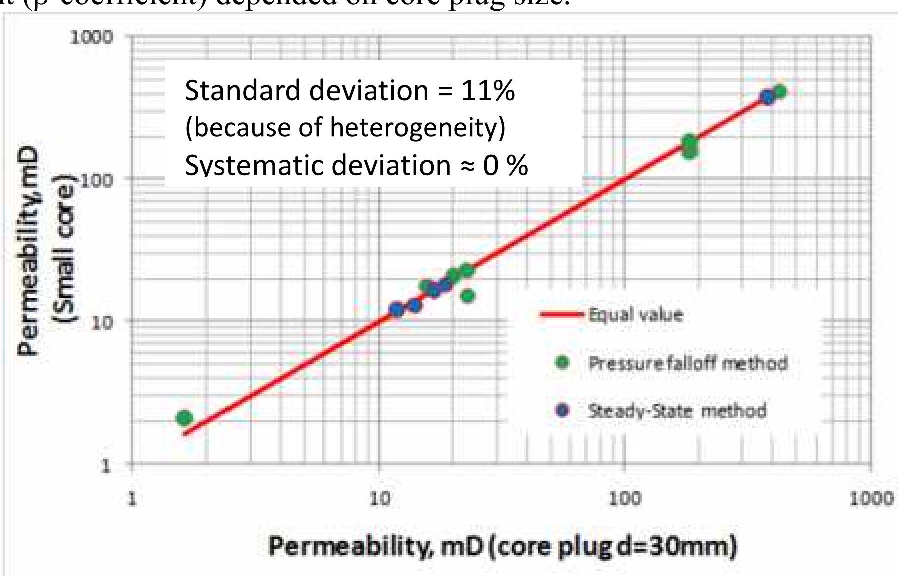

Fig. 4. Comparison of permeability values measured on mini-plugs and Ø30 mm core plugs.

ONE AND TWO-PHASE FLOW EXPERIMENTS

For core flooding experiments on mini-plugs we built a Hassler-type coreholder with electrodes for electrical properties measurements by two-wire method [3]. Steady-state technique was used for permeability measurements. Initially we tested our multiphase coreflooding system at single phase flow. Our numerous tests on coreflooding with brine, decane, kerosene and oil demonstrated that for more or less homogenous terrigenous rock the downscaling of core plug size from Ø30 to Ø8 mm did not cause any significant changes in permeability at least for rock in range 5–1500 mD. The reason is that tested mini-plug is much bigger than length scales of various physical processes [4, 5]. Performing routine measurements on Ø8 mm plugs we discovered some advantages of using mini-plug for conventional core analysis: (1) reducing amount of fluids and time required for experiment; (2) it allows performing measurements on several plugs from different parts of full size core and thus takes into account rock heterogeneity or anisotropy.

We spent some efforts on measuring two-phase permeability curves by steady-state technique. For these types of experiments we prepared mini-plugs with length about 30 mm. Here we faced with the following expected issues: separation of fluids at core inlet which followed by slug flow; capillary end effects; fluid saturation estimation.

In overall, mini-plug saturation can be estimated with high quality by NMR or micro-CT with contrast agent. Mass balance method is not applicable here because of pore volume of mini-plug is comparable or even less than resolution of the method (0.1 cc). We calculated mini-plug saturation with Archie equation using electrical resistivity data. Saturation exponent was obtained from measurements on Ø30 mm core plug.

We started our search from the simplest porous media – Bentheimer sandstone with gas permeability about 2800 mD. When oil (decane) and water (brine, 20 g/l of NaCl) phases were mixed in T-valve and flowed through OD 1/8″ steel tube (simplest coreflooding setup) we observed a huge oscillation of pressure drop and saturation (that is resistivity). It corresponded to slug flow i.e. sequences of drainage/imbibition cycles. It is interesting to note that extreme values of pressure drop and saturation were close to end points of relative permeability curves. To provide homogeneity of fluid flow we installed mixers at inlet and outlet. The best option for these high permeable plugs turned out to be a stack of 3 stainless steel filters with mesh size 100, 50 and 15 μm and thickness about 5 mm each. This combination of filters did not affect to pressure drop and, at the same time, reduced the oscillations and allowed obtaining reasonable data on phase permeability (fig. 5) comparable with reference curves. As a reference data, we used relative permeability curves measured on Ø30 mm (fig. 5) with the same pair fluids, at the same PT conditions by steady-state method [3]. Increase in flow rate also helped us to reduce capillary end effect [6 ,7] and made flow at inlet more homogeneous.

CONCLUSIONS

(1) Conventional technique with a little hardware and methodology modifications can be used for mini-plug characterization.

(2) Reduction of core plug size from few centimeters to several millimeters does not change their properties drastically for rather homogenous samples we studied, and difference between measurements on standard plugs and mini-plugs does not exceed experimental uncertainty.

(3) Measurements of permeability on mini-plugs allows saving fluid volume and time consumption, as well as to study single phase flow in non-Darcy regimes using pumps with relatively low flow rates (up to 30 cm^3/min in our case).

(4) Relative phase permeability can be measured on mini-plugs only if homogeneity of inlet fluid flow is provided.

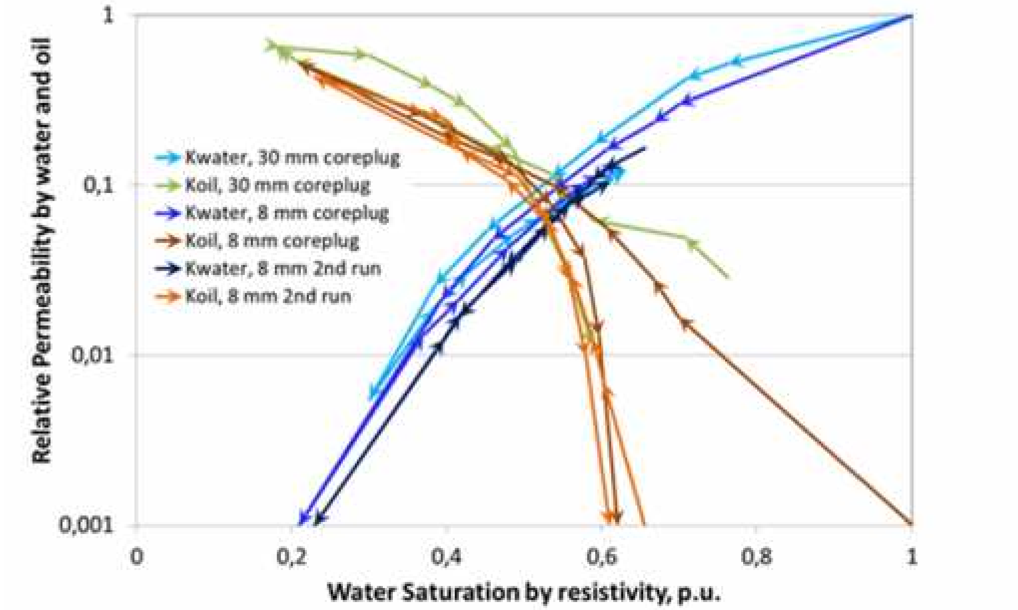

Fig. 5. Relative phase permeability curves of Bentheimer sandstone measured on mini-plugs and Ø30 mm core plugs.

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