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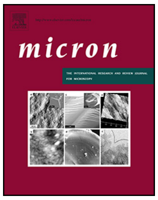

Rock porosity quantification by dual-energy X-ray computed microtomography

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ABSTRACT

Porous media investigation by X-ray microtomography allows obtaining valuable quantitative and qualitative information, while preserving sample integrity. Modern X-ray nanotomography or Synchrotron radiation systems may distinguish structures sized only hundreds of nanometers. However, pores sized less than a few microns (microporosity) may be undetectable due to the system's spatial resolution and noise in microfocus sources, compromising the quality of the measurement. In this study a dual-energy methodology was developed to generate density-based images from two scans made at two different voltages (80 kV and 130 KV) with a microfocus bench-top microtomography system. The images obtained were quantized in 256 gray levels, where the lowest value (zero) corresponded to voids and the highest value (255) corresponded to the densest regions mapped. From density images and single energy images, porosity was evaluated and compared. Results indicate that density images present better results than single energy images when both are compared with porosity obtained by the helium injection method. In addition, images acquired in dual-energy show good agreement with the sample's real density values.

1. Introduction

X-ray computed microtomography (microCT) is a powerful technique applied to analyze the internal structures of objects. Since it is a non-destructive test, it allows assessing the samples preserving their integrity. This is a valuable attribute, if the study requires to submit the same object to various assays (Kim et al., 2013; Zabler et al., 2008). The main advantage of microCT over other non-destructive techniques is that it provides three-dimensional images and quantitative results. Although the chemical composition may not be accessed directly, image acquisition is based on the attenuation coefficient, which depends on the energy of the X-ray beam that passes through the sample, its density and atomic number (Attix, 1986). MicroCT reconstruction produces a 3D gray-level image, where the data are stored as a stack of 2D sections, slices, allowing accessing any region of the object.

Developed through recent decades, microCT has been used in many scientific fields. One of the most important contributions of microCT is to geosciences and petrophysics, where the technique is widely used in the analysis of fluid flow and the performance of injected diverting agents (A.C. Machado et al., 2015; Ribeiro et al., 2007; Wennberg et al., 2009), analysis of porosity and internal structures (A.S. Machado et al., 2015; Cilona et al., 2014; Vergés et al., 2011) and mineral component identification (Long et al., 2009), among many other applications. In the petrophysical field, characteristics such as porosity and rock capacity to store fluids, help to define the best technique for the exploration of oil and gas reservoirs based on pore and void structure. Empty spaces are detected by microCT due to the low attenuation suffered by the X-ray photons in these regions.

Indeed, many problems arise in microCT image acquisition (Cnudde and Boone, 2013). Artifacts such as beam hardening effect which is due to the polyenergetic nature of the beam may be reduced by metallic filters positioned in front of the X-ray source and by correction software during image reconstruction (Barrett and Keat, 2004; Ketcham and Hanna, 2014). Other issues, however, do not have clear-cut solutions. In heterogeneous rocks, some matrix components are indistinguishable in microCT images because the values of the attenuation coefficients are very close. The precision of these measurements is directly influenced by the spatial resolution of the microCT system. The partial volume effect, in which a voxel is represented by the gray value of the average attenuation coefficient of the materials composing it, affects the accuracy of the measurement. In these cases, dual-energy microtomography (DE-microCT) emerges as a solution. To obtain useful information that can help characterizing the scanned object, two

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images at different energies are used exploring the different ways in which X-ray photons interact with matter (Hsieh, 2009).

The aim of the present study was to evaluate images obtained by the dual-energy technique, described in Section 2. To this end, three homogeneous rock samples were scanned in a bench-top microCT system at two different energies, and their images were constructed based on sample density. Density values were evaluated in the images obtained to corroborate the validity of the dual-energy methodology. Finally, porosity was evaluated and results were compared with porosity values obtained by the Helium (He) injection method.

2. Dual-energy microct

According to Beer's law, the relationship between incident X-ray I_0 and attenuated X-ray I, for monochromatic sources, is given by Eq. (2.1), in which x represents the objet thickness and μ is the linear attenuation coefficient.

$$I = I_0 e^{-\mu x}, \tag{2.1}$$

The total linear attenuation coefficient μ can be decomposed into the contributions from each mode of photon interaction with matter (Cesareo, 2000). In the energy range used in microCT, below 100 KeV, photoelectric effect and Compton scattering are the two dominant processes of X-ray interaction with matter. The first one is predominant at low-energy values while the second effect is more prominent at medium-energy values. These effects are related with the density ρ and the effective atomic number Z of the object in different ways. While photoelectric effect probability increases rapidly with Z and ρ, at the same time that decreases with photon energy E, Compton scattering probability is ρ and E dependent. In this context, the attenuation coefficient μ may be described by Eq. (2.2), in which a and b are energy dependent constants and the photoelectric effect and Compton scattering are represented by the first and second terns, respectively (Dyson, 1990).

$$\mu_E = \rho \left(a_E Z^{3.8} + b_E \right) \tag{2.2}$$

However, if a given object is scanned in microCT twice at different energies, but preserving the same position, based in Eq. (2.2), the following Eqs. (2.3) and (2.4) may be set up, in which E_1 and E_1 mean low and medium energies, respectively.

$$\mu_{E_1} = \rho \left(a_{E_1} Z^{3.8} + b_{E_1} \right) \tag{2.3}$$

$$\mu_{E_2} = \rho \left(a_{E_2} Z^{3.8} + b_{E_2} \right) \tag{2.4}$$

The energy constants presented in Eqs. (2.3) and (2.4), a_{E_1}, a_{E_2}, b_{E_1} and b_{E_2} may be obtained by using standard materials whose ρ and Z are completely well known, and since these values are defined, Eqs. (2.3) and (2.4) provide the resultsshown in Eqs. (2.5) and (2.6) (Van Geet et al., 2000, 2001).

$$\rho = \frac{b_{E_2}\mu_{E_1} - b_{E_1}\mu_{E_2}}{b_{E_2}a_{E_1} - b_{E_1}a_{E_2}} \tag{2.5}$$

$$Z = \left(\frac{a_{E_1}\mu_{E_2} - a_{E_2}\mu_{E_1}}{b_{E_2}\mu_{E_1} - b_{E_1}\mu_{E_2}} \right)^{1/3.8} \tag{2.6}$$

This is the approach of DE-MicroCT, which is based on the different ways that the X-ray interacts with matter. In ordinary single energy microCT scan, an image is represented by gray levels related with μ, which is a combination of ρ, Z and E. However, in DE-microCT, the real values of ρ and Z can be obtained.

3. Materials and methods

The samples selected for this study were reservoir rock plugs, which were previously assayed by He injection in order to obtain porosity measurements of standard packings. Samples of Indian Limestone, Silurian Dolomite and Idaho Gray Sandstone are shown in Fig. 1, totaling $n = 3$, and their main characteristics are described in Table 1. Samples 1 and 2 are carbonate rocks and sample 3 is an example of typical sandstone. The first type presents a wide spectrum of particle sizes, high primary porosity and mineral composition chemically unstable. These characteristics are responsible for a complicated diagenesis, which impairs water, oil and gas location within it. On the other hand, the second type, highly porous, often an aquifer or petroleum reservoir, has a more uniform stratigraphy and petrophysical character being its geometry and reservoir performance more predictable when compared with the first (Selley, 2000).

MicroCT images were obtained in a microfocus bench-top system (Skyscan/Bruker, 1173 model) with two different tube voltages, 80 kV/100 µA (energy E_1) and 130 kV/60 µA (energy E_2) and a 50 µm flat panel X-ray sensor C7942SK-25 (Hamamatsu Photonics, Japan) with 2240 × 2240 pixel matrix. E_1 and E_2 values were chosen targeting an energy difference as large as possible, while keeping sufficient transmission and absorption for reasonable image reconstruction. The scans were performed sequentially, without removing the sample from the sample holder, in order to obtain sample images at the same position to be used in the DE-microCT methodology. Each image projection, in both energy configurations, was averaged from five frames. The sample was rotated at 0.5° steps until a rotation angle of 360°. These processes generated 720 images with pixel size of 25 µm in total time of 1.25 h.

A copper filter with 0.5 mm thickness together with tube voltage settings enhanced the separation between X-ray spectra. The filter must be chosen aiming at approximating the spectrum to a monoenergetic one, removing low energy X-rays, with no significant loss of intensity. In addition, metallic filters at the exit of the X-ray tube attenuated the low energy photons, which are responsible for the beam hardening artifact. The energy values adopted in this study are in accordance with the system configuration and sample characteristics. The Highest energy is the maximum energy supported by the X-ray source and the lowest energy is sufficient for the photons penetrating the material. In this setup, based on Xcom data (Berger et al., 2010), the photoelectric effect is predominant at low energy, and Compton scattering is the main effect at medium energy, although the photoelectric effect is also present.

Image reconstructions were performed by the commercial software NRecon v. 1.6.10 (Skyscan/Bruker)/Instarecon (instarecon®CBR), which is based on Feldkamp algorithm, an analytical reconstruction method applied to image reconstruction from cone-beam filtered back projections (Feldkamp et al., 1984). For each pair of scans, at low and medium energies, the same region of interest (ROI) was defined (1600 axial slices), which corresponded to a sample height of 40 mm, approximately. Image correction parameters, such as beam hardening and ring artifact corrections and contrast limits were defined independently for each sample scan because it is practically impossible to keep the same parameters for a large energy range (Bruker microC.T., 2013).

Low and medium-energy microCT image stacks were combined according to Eqs. (2.5) and (2.6) in order to obtain density calibrated microCT images. For this purpose an in-house computational code using MATLAB was used. The energy constants, a_{E_1}, a_{E_2}, b_{E_1} and b_{E_2}, were obtained in accordance with Alves et al. (2014) and Alves et al. (2015), whose principle is based on the graphical interface between $\left(\mu(E)/\rho\right)$ and $Z^{3.8}$ from a group of homogeneous minerals. The minerals used in this study are shown in Table 2. As a result of image processing, the DE-microCT final images are presented using 256-gray-levels, where the lowest value (zero) corresponds to voids and the highest value (255) corresponds to denser pixel regions. To validate the assay, the theoretical and DE-microCT density values of the rock samples were compared. It is important to note that