Applied Radiation and Isotopes 110 (2016) 160–163

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Porous media investigation before and after hydrochloric acid injection on a pre-salt carbonate coquinas sample

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HIGHLIGHTS

- Porous space characterization is an important data of the carbonate reservoir.
- Microtomography provides quantitative information about rock porous network.
- Characterization of internal rock structures as wormhole formation.
- Different image processing programs can be used to quantify the porous space.

ARTICLE INFO

Article history:
Received 18 May 2015
Received in revised form
18 December 2015
Accepted 5 January 2016
Available online 6 January 2016

Keywords:
X-ray
Microtomography
Coquina
Carbonate
Pre-salt
Porosity

ABSTRACT

Porous space characterization of carbonate rocks is an important aid in petroleum exploration from carbonate reservoir. In this study, X-ray microtomography technique was applied to evaluate total porosity of a coquina sample extracted from pre-salt reservoir, in Brazil, before and after acid injection. Two image processing program were used in order to assess performance. The results showed that microtomography has potential to compute porosity of coquina samples and provides information about rock porous network.

1. Introduction

The pre-salt region on southeast Brazil coast was originated around 160 million years ago, during the separation of South America from Africa. The deposition of sediments and the sea water created conditions for the growth of special bacterial colonies. The secretion of these bacterial and precipitations of carbonate salts formed the carbonate rocks in the regions where the oil was found. Important oil reservoirs in Santos basin (Brazil coast), representing a huge volume of oil and gas, are composed of coquina, a sedimentary rock that is composed either wholly or almost entirely of the transported fragments of the shells of mollusks or other invertebrates. Coquina reservoirs present a major challenge for exploring new wells, since they are apparently heterogeneous and poorly understood with few similar around the world (Nakano et al., 2009). In this context, the study of coquina reservoir behavior is essential to enable the exploration of resources, mainly in order to improve the productivity of wells.

Acidizing is a widely employed technique to optimize oil and gas extraction by improving the permeability and has been very successful in carbonate reservoirs (Liu et al., 2012). In this process, the injected acid infiltrates in the walls of the well enlarging and connecting the voids. In general, this will form a channel, known as wormhole (Bazin, 2001; Hoefner and Fogler, 1988). In low-permeability carbonate reservoirs, hydrochloric acid (HCl) is more recommended to acidizing process, which is capable to dissolve calcium carbonate easily (McLeod, 1984). Through a high reaction hate of acid, the wormhole extend radially into the rock enlarging and connecting the pores (Siddiqui et al., 2006).

Investigating the acid effect on the porous media of coquina rock is necessary to develop better procedures for oil extraction

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http://dx.doi.org/10.1016/j.apradiso.2016.01.005
0969-8043/

from the pre-salt reservoir. X-ray computed microtomography (micro-CT) has potential to give insights about the petrophysical characteristics of carbonate rocks because it provides high resolution images of pores and differentiable mineral phases (Oliveira et al., 2012).

The micro-CT consists of performing a series of radiographics under different angles, thereby producing enough information to algorithmically reconstruct a 3D X-ray attenuation map of the sample. One of the main advantages of micro-CT is the non-destructive nature of the technique. It allows one to investigate the interior of an object without sacrificing it.

The recorded images represent a mapping of the detected X-ray attenuation, and during the image acquisition process, the sample is rotated in regular steps generating one radiographic image by step. The visibility of the various features of an object depend on the spatial resolution with which they may be imaged and on the contrast, the features have relative to their surroundings. The dynamic range within the projections is extremely important in dictating the levels of contrast that can be retrieved reliably from reconstructions (Stock, 2008). The radiographic images are reconstructed to form an image using filtered back projection. Analysis suggests that $q\pi/2$ projections are required where q is the number of detector pixels horizontally, such that for a 2048-pixel detector around 3200 projections are recommended. This has developed from the original fan beam technique providing a single tomographic slice (Maire and Withers, 2014). The Feldkamp algorithm is a widely used cone beam filtered back projection algorithm that can be regarded as a natural extension of the fan beam case (Feldkamp et al., 1984).Finally, after reconstruction it is possible to extract information about the sample by specific analysis program. In this study, two different programs were used to quantify the porous space of a coquina sample before and after acidizing and their results were compared.

2. Methodology

The rock core sample used in this study was collected at a quarry in North East Brazil (position: 9° 45′ 33.93″ S-36° 9′ 17.67″ W). The core dimensions were 25.4 ± 0.2 mm of diameter and 87.9 ± 0.2 mm of height and it was named 3-1 sample. The core suffered HCl acid injection in Formation Response Tester (FRT). This equipment can hold two different diameter cores, 0.025/0.038 m and up to 0.304 m long and pressure and temperature can reach 34.47 MPa and 148.9 °C, respectively.

Micro-CT images were obtained by using a microfocus desktop system operated at 130 kV (8 W).The core was rotated in steps of 0.5° until a rotation angle of 360° was completed, which generated 720 shadow projections with a pixel size of 20.2 μm using a flat panel sensor system with 2240 × 2240 pixel matrix (Hamamatsu C7942SK-25). However a minimal number of projections is recommended, total time of acquisition is related by exposure time, number of angular steps and number of frames (Van Geet et al., 2001), in this sense, it is necessary to adopt one value for this parameter that provides good results without time-consuming. In this study, the set-up adopted is based at previous works using similar samples (Machado et al., 2014), where a total scanning time of 180 min for each core was reached. An aluminum filter of 1.0 mm thickness was used between the X-ray source and the sample to reduce beam hardening artifact caused by lower energy photons attenuation. The shadow projections were rebuilt using NRecon® (Skyscan/Brucker, v.1.6.9.4) and Instarecon® (Skyscan/Brucker, v.1.3.9.2) program performing adjustments to obtain high quality images (Machado et al., 2014). The algorithm of this program is based on Feldkamp algorithm (Feldkamp et al., 1984). Gaussian smoothing filters with degree of 2, a ring artifact reduction with level of 10 and a beam hardening artifact correction with a degree of 35% were the parameters used to reduce artifacts. The total reconstruction time was about 95 min for each rock sample.

Two image stacks (approximately 6.8 GB each one) corresponding to the rock core before and after the acidizing procedure were generated. MicroCT raw data is shown in a gray level scale and the histogram of these ranges shows the number of pixels distributed on image established for each gray level from darkest (corresponded to 0) to brightest (corresponded to 255). For many analyses, micro-CT gray scale rock images must be segmented and in this study this procedure was performed by grayscale thresholding. In general, whereas the image has two phases, a minimum value between two peaks in the grayscale histogram of the reconstructed data is sufficient to obtain good structure segmentation. In other work, the object of interest has to be marked. Pixels lower than the threshold value represented empty space (bright areas) while pixels with higher values characterized the object. Therefore, the binary image is created. The main goal of the segmentation process is the separation of the raw image into distinct regions with a correct threshold value. One of the difficulties lies in the polychromatic nature of the beam from the X-ray tube, which the number of its detection varies in a Gaussian distribution. As mentioned above, the histogram of microCT image is used to determine the distribution of percentage of each material present in the sample. In this sense, the range of grays may or may not be overlapping leading in a non accurate threshold determination. Consequently, perfect image separation is a goal that cannot usually be achieved. Thresholding is perhaps the most frequently used procedure to segment an image and, after this operation, the gray levels are remapped to a binary image. In this sense, a suitable threshold level is required, otherwise over or under segmentation can occur. Neither of them contributes to a good image quality characterization since pixels belonging to the same object (or region) are classified as belonging to different segments or vice-versa. A threshold intensity value was defined in order to extract all the solid objects present in the core samples. A global threshold was applied and an optimal value T was chosen by overlapping the original image (gray scale) with the segmented image (black and white – binary). Subsequently, the void space was represented as black pixels while all remaining objects were denoted as white pixels. After proper segmentation a stack of binary images was obtained and the phase volumes were evaluated in order to determine total porosity. 2D or 3D approaches can be used in order to get good quality results, two program development methodologies were used; Avizo Fire® (Visualization Science Groups, v.7.1) and SkyscanCTAn® (Skyscan/Brucker, v.1.13.11).

Total porosity (%) and pore diameter were computed based on a surface-rendered volume model (Lorensen and Cline, 1987). However, other parameter, such as,the space between the pores, named pore separation, were also evaluated but now in a 2D approach. This parameter is essentially the thickness of the space between the pores within the volume of interest (VOI) in all selected image levels, slice-by-slice.

In order to estimate the influence of wormhole formation in pore space connectivity, the fragmentation index (Fr.I) was evaluated. This parameter was first defined for trabecular bone (Hahn et al., 1992) applications in which FrI described the connectedness of individual trabeculae in a 2D section. In other words, for our study it means that lower FrI signifies better connected rock lattices while higher FrI means a more disconnected rock structure. This line of thought is correct, in the binary image, white pixels will be represented by the rock structures. In this sense, in a 2D look, FrI can be calculated taking into account the solid perimeter and area before and after image dilatation procedure. This is