Reservoir Rock Microstructure Evaluation by X-ray Microtomography

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***Abstract*—The objective of this study is to evaluate the quantification process of geometric parameters such as material volume, when different computed microtomography spatial resolutions are employed. To this end, two reservoir rock samples were scanned with a three-dimensional high energy computed microtomography system. The results show a strong difference in the acquisition, reconstruction and image processing times, but do not present a significant loss of information on the micro structural parameters such as porosity between the two resolutions.**

Keywords-X-ray; microtomography; rock.

I. INTRODUCTION

High resolution 3D computed microtomography (microCT) is a powerful technique used to visualize and characterize the internal structure of objects. It is a non-destructive method that produces images of the internal structure of an object which does not need to be previously modified, i.e., the object inspected does no need to be subjected to a preparation method such as impregnation, thinning or polishing [1]. In this technique, contiguous sequential images are compiled to create 3D representations that may be digitally processed to obtain relevant quantitative geometric and/or morphologic parameters, depending on the focus of the investigation [2]. The great advantage of microtomography is that quantitative information such as volume, size, shape, distribution and connectivity of the rock pores can be obtained through the entire 3D volume of the samples, from micro-scale to nano-scale.

MicroCT physical principle is based on the attenuation of X-rays when they interact with the object. The intensity of the photons crossing the object depends on the number of atoms by volume unit (density) and on the type of the atoms throughout the beam. In order to obtain the image of a section of a test specimen it is necessary to obtain many projections in constant angular steps [3]. Beam hardening artifacts in gray level, which may show up in the images, manifest due to the preferential attenuation of low energy photons. This process can be minimized using metallic filters to eliminate low energy photons from the incident radiation. When the object is a rock sample it is common to insert a combination of two metallic filters such as aluminum and copper [4].

It is know that the better the spatial resolution of the images in microCT the better the visualization of small details. However, the quantification of structural parameters in microCT is extremely dependent on image resolution, which may affect final data interpretation [5-7].

The objective of this study is to evaluate the changes that occur in the entire quantification process (acquisition, reconstruction and processing) of geometric parameters, such as porosity, of reservoir rocks when different image resolutions are employed. For that purpose it will be used high resolution microCT equipment and several holes in two rocks will be the focal point of this investigation.

In the next sections it will be described all the experimental conditions that the carbonates were submitted, as well as the methodology used to characterize the rocks. The geometric parameters used in this study were the total volume of the binary-converted objects within the volume of interest, the percentage of the volume of interest occupied by binary, the total porous space volume and total porosity. After that section, for each experimental condition and imaging processing, the results are analyzed and discussed and the 3D microCT visualization will be presented together.

II. MATERIALS AND METHODS

The reservoir rocks used in this study are of the carbonated type and were named samples 1 and 2 (Fig. 1). Five holes were made in the sample 1 and nine holes in sample 2, in a way that their dimensions are known. Thus, it is possible to evaluate the accuracy and precision of 3D quantification by microCT.

MicroCT's were obtained in a high energy microtomography system (Skyscan/Bruker, model 1173). The samples were placed in the experimental equipment inside an acrylic cylinder with a 1.0mm thickness for sample 1 and a 3.1mm thickness for sample 2. This ensured that the samples would not move during the entire acquisition process, which lasted about 1 or 2 hours, depending on the resolution used.

The system was calibrated to operate at 130kV of energy and a current of 61 μA. The microCT system has 2 built-in metallic filter options: aluminum (with a thickness of

1.0mm) and brass (0.15mm thick). The intention of these filters is to reduce the contribution of low energy photons to minimize the effects of beam hardening. In the present study, a combination of two filters was used: copper (0.15mm thick) and aluminum (1.0mm thick).

The spatial resolutions used in this study were 10 µm and 20 µm. In these conditions the distances source- sample and source- detector were of 72.8mm and 291.2mm for the 10µm resolution and of 148.3mm and 215.7mm for the 20µm resolution, respectively. A flat panel detector was used (2240 x 2240 pixels) to register the cone X-ray beam transmission. The projection images were taken 360º at each step of 0.50º rotation.

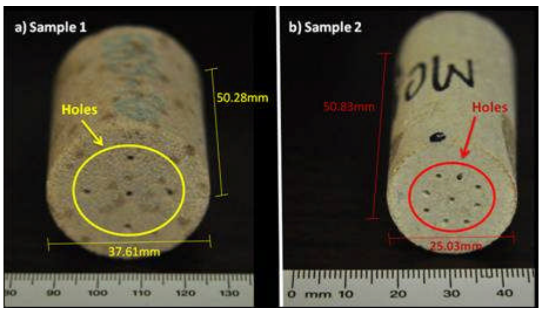

Figure 1. (a) photograph of sample 1 with their dimensions and the holes in the spotlight and (b) photograph of sample 2, also with their dimensions and the holes in the spotlight.

After the acquisition process, the radiographic images were rebuilt. For such, Nrecon ® [08] - version 1.6.4.1 and InstaRecon [09] - version 1.3.5.0 softwares were used, the algorithm of which is based on the works of Feldkamp [10]. The reconstruction software used allows the selection of many parameters thus creating a better quality image. Artifact corrections can be made in the image such as correction of the ring artifact that shows up as total or partial rotation-axis centered circles, caused by changes on the output of individual detectors or set of detectors. Corrections of beam hardening can also be made, which turns the object borders shinier than the center even in homogeneous materials since low energy X-rays are attenuated more promptly than high energy X-rays.

The most important parameters are the use of smoothing filters in different degrees (1 to 10), reduction of ring artifacts in different levels (1 to 20) and beam hardening correction in different levels (1% to 100%). In this study, Gaussian smoothing filters with degree 1, a ring artifact reduction with level 15 for sample 1 and level 10 for sample 2 and a beam hardening artifact correction with a degree of 20% for sample 1 and of 25% for sample 2 were used. The Kernel Gaussian smoothing filter is characterized as a smoothing applied to projections. It smoothes each pixel with a MxN neighborhood, where M is the horizontal dimension and N the vertical dimension. It reduces noise and searches for a proper smoothing level. Ring artifact reduction is also applied to projection before image pre-processing so that the average projection is used for this purpose. It is possible to select the depth of this correction in a 1 to 20 pixel gap. Beam hardening can be obtained through linear transformation and depth correction can be chosen according to the material density. A high order in the polynomial function can also be used for this purpose.

The Skyscan, CTAn ® [11] (v.1.11.8.0) software was used for image processing and analysis. In this stage the objective was to quantify geometric parameters related to the holes created in each of the samples at the laboratory. These holes were made with a 0.9 mm wide drill in sample 1 and a 1.0 mm wide drill in sample 2. Thus, the final dimension of the holes drilled were of 9.3 mm, 3.7 mm, 3.4 mm, 3.0 mm and 4.1 mm depth for sample 1 and of 9.0 mm, 4.9 mm, 3.5 mm, 4.5 mm, 4.0 mm, 4.4 mm, 4.1 mm, 4.35 mm and 4.3 mm depth for sample 2. Considering a cylindrical geometry and disregarding the narrowing obtained at the end of each hole it is possible to say that the volume of the holes were 14.92 ±0.02 mm^3 in sample 1 and 33.75±0.02 mm^3 in sample 2. The quantified parameters were: total volume of the binary-converted objects within the volume of interest, VOI, (BV, mm^3), percentage of VOI occupied by binary objects (BV/TV, %), total porous space volume (Po. V(tot), mm^3) and total porosity percentage (Po.(tot), %).

A region of interest (ROI) that contemplates both holes in each sample and in each resolution was defined to conduct the quantifications. All objects inside the ROI were analyzed. In this study, circular ROIs with a diameter equal to 23.16mm and 14.48mm for samples 1 and 2, respectively, were used.

It is important to highlight that a threshold (TH) value separating both objects comprised in the ROI must be chosen for the quantification process. There is no standard method to determine the TH value. In this study a global TH value equal to 30 was used, considering a 0 to 256 gap. Thus, we could separate the pores (white) from the rock matrix (black). Then, the parameters where quantified directly in 3D based on a model of the rendered surface volume. All objects in the selected region were analyzed together and the integrated results were calculated as the total volume of all objects.

III. RESULTS AND DISCUSSIONS

The acquisitions generated data matrixes of 4224 x 4224 pixels and of 2240 x 2240 pixels for the 10 µm and 20 µm resolutions, respectively. Such matrix sizes have the disadvantage of being too difficult to be processed; especially by microCT once their files can reach a 34.7GB size (1200 images for each microCT test). Aiming to improve the time for image processing the images passed through a resize process before they were quantified. This process allows reducing the size of an image and of a data set by the average of voxel gray levels in a cube of specified size. For example, resizing in a 2 factor opens a version of the data set with 8 times less voxels (2x2x2). This allows a very quick handling, geometric measuring and the construction of models of lower spatial resolution. In this study resizes of 2 and 4 were used.

Tables I-IV show the time for image processing obtained in each condition used. The quantifications showed in Tables III-IV were made based on the values of the matrixes presented in Tables I-II. These numbers take into consideration the entire volume of the holes, which are the objects of interest in this study.

TABLE I. MICROCT DIFFERENCE IN IMAGING ACQUISITION AND RECONSTRUCTION TIMES

Samples	Acquisition Resolution	Acquisition	Reconstruction
		Scan duration	*Duration per slice*
Sample 1	10 µm	02:02:40 h	2.0 s
	20 µm	00:59:12 h	0.4 s
Sample 2	10 µm	01:55:48 h	1.5 s
	20 µm	00:59:44 h	0.3 s

TABLE II. MICROCT DIFFERENCE IN IMAGING PROCESSING II

Samples	Acquisition Resolution	Processing		
		Original Matrix	*Quantified Matrix*	*Slice Numbers*
Sample 1	10 µm	4224 x 4224	(resize 2x) 625 x 625	145
	20 µm	2000 x 1932	(resize 3x) 614 x 614	143
Sample 2	10 µm	4224 x 4224	(resize 3x) 829 x 829	224
	20 µm	1356 x 1296	(resize 2x) 612 x 612	221

TABLE III. MICROCT RESULTS - SAMPLE 1

Parameters	Resolutions		
	20 µm (Original)	*Resize 2x*	*Resize 3x*
Matrix quantified (pixels)	2000X1932	625x625	614x614
Object binarised Volume (mm^3)	23.34	16.2	14.25
Percent object volume (%)	0.64	0.40	0.39
Total volume of pores (mm^3)	3623.2	3599.8	3613.5
Total porosity (%)	99.4	99.6	99.6

TABLE IV. MICROCT RESULTS - SAMPLE 2

Parameters	Resolutions		
	20 µm (Original)	*Resize 2x*	*Resize 3x*
Matrix quantified (pixels)	1356X1296	829x829	612x612
Object binarised Volume (mm^3)	27.59	36.50	27.19
Percent object volume (%)	1.91	2.50	1.86
Total volume of pores (mm^3)	1416.8	1423.2	1427.3
Total porosity (%)	98.1	97.5	98.1

As expected, this table shows that the higher the spatial resolution the higher the time required for the data to be obtained. However, when resize is used there is the need to consider the change in the pixel's size, which may impair the quantification of small structures. In this case, the size of the pixel is increased, making us 'see' only the structures from this new value, which leads us to analyze the cost/benefit of this procedure.

Tables III-IV show the results of the geometric quantifications for 20 µm resolutions in both samples with different pixel sizes obtained through the resize process and without resize. Being the real volumes of the holes 14.92 ±0.02 mm^3 in sample 1 and 33.75 ±0.02 mm^3 in sample 2 there is no significant difference in relation to the values quantified in the 3D analysis.

The difference of less than 1% in the results of the percentages of each parameter calculated in the 3D analysis, of each sample between resolutions, is noticeable. Thus, when necessary to characterize objects with the dimension of the holes assessed in this study, a microCT test in the quickest acquisition and image processing conditions can be used since losses in the data obtained wee not significant. Obviously, the smaller the size of the pixel the more detail can be visualized in the image, generating more precise and accurate quantitative results.

The tridimensional models built after the 3D analysis of the holes may be observed in Fig. 2 and Fig. 3.

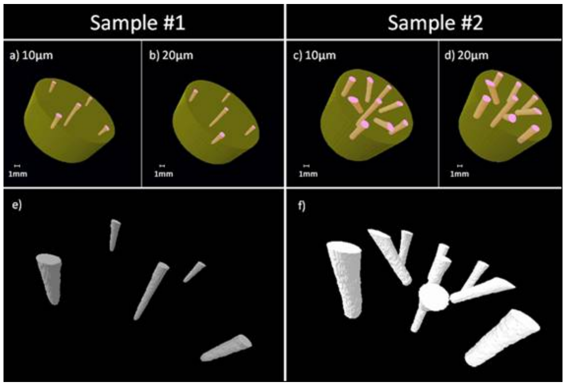

Figure 2. 3D models of sample 1 in the resolution of 10µm (a) and of 20µm (b) and of sample 2 in the resolution of 10µm (c) and of 20 µm (d). Better views of the holes for sample 1 (e) and sample 2 (f).

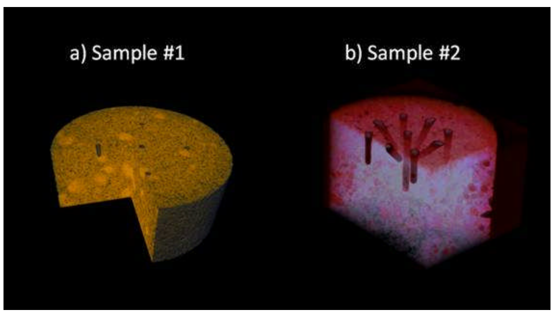

Figure 2. 3D models of sample 1 in the resolution of 20µm (a) and of sample 2 in the resolution of 20µm (b).

IV. CONCLUSION AND FUTURE WORK

The 3D Computed Microtomography technique is adequate for the characterization of reservoir rocks, supplying internal micro structural parameters that allow the petrophysical study of these materials. The differences presented in all stages (acquisition, reconstruction, processing and analysis) show that for a high resolution long acquisition and reconstruction periods are needed and processing is difficult, demanding the use of resize. This pixel size reduction tool proved to be very useful since it optimizes the analysis process not causing a significant loss of information. The next stages of this work is to analyze all the pore space of rocks, not only the created holes and further investigate the metrology associated with parameters related to the porosity space.

ACKNOWLEDGMENT

The authors would like to thanks CNPQ, FAPERJ and Petrobras/CENPES.

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