THREE DIMENSIONAL CHARACTERIZATION OF MATRIX ACIDIZING BY X-RAY COMPUTED TOMOGRAPHY

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ABSTRACT

Tight carbonate reservoir rocks are increasingly being acidized to etch flow paths and create wormhole networks to increase oil and gas productivity. Dissolution of rocks along the path of acid flow has been shown to increase porosity and permeability thereby leading to enhanced recovery. Understanding the geometry of wormholes and quantifying the amount of dissolution will enable better and more efficient acid stimulation programs in both acid fracturing and in matrix acidizing. Many reported experiments characterize wormholes in one-dimension (1-D) and provide little information on the change in porosity as a function of pore volume and pore structure. However, fluid flow in a reservoir is a three-dimensional (3-D) phenomenon, and directly related to pore connectivity. Understanding the geometry of wormholes in 3-D as well as quantifying the change in rock porosity as a result of acid treatment is pertinent for the design of effective acid stimulation. This paper presents the visualization of worm holes in 3-D and quantification of the change in porosity using X-ray computed tomography. Four carbonate plug samples were scanned before and after acid treatment, with the post-treatment images being spatially registered to the pre-treatment images. Subtracting the registered post-treatment images from corresponding pre-treatment images provided sets of difference images which illustrated the geometry of the generated worm holes in 3-D. The change in porosity of the plugs were determined by calibrating the grayscale values of the difference images against the grayscale values of the sample matrix from the pre-acid treatment images. Results demonstrate the formation of a single principal wormhole from top to bottom in all four samples. The wormholes were non- linear but followed a tortuous path which can be correlated with compositional and structural changes in the samples. The change in porosity ranges between 1% and 3%. The datasets from this work provide a qualitative and quantitative assessment of acid treatment and can be used as inputs into acid stimulation models to produce better results.

INTRODUCTION

In the continued quest to boost the supply of energy resources worldwide, exploitation of oil and gas within tight carbonate reservoir rocks are increasingly being addressed. The low permeability of these types of rock presents the greatest challenge to their successful exploitation. However, the high solubility of these rocks in acid enables the use of acid stimulation to enhance flow pathways to the wellbore. The ultimate aim of acid stimulation is the generation of wormholes, which are defined as highly conductive flow channels that connect near well regions to the completion [1]. The generated wormholes lead to an increase in permeability, thereby enhancing the production potential of a well.

Factors such as acid concentration, injection rate and temperature, as well as peculiar rock properties such as composition and porosity play important roles in wormhole formation. Furthermore, fluid transport in rocks is in three-dimensions (3-D), as such; the characterization of wormholes geometries in 3-D is pertinent to the proper planning of acid stimulation programs. However, most experimental work on matrix acidizing involves linear assumptions due to limitations in extracting 3-D data. Works that have reported 3-D insights into wormholes generation [1, 2] have been mostly qualitative. Quantitative measurements of the changes in porosity, path length and volume are valuable in the overall characterization of wormholes.

Computed Tomography (CT) imaging, which is a non-destructive technique, can be used to visualize the internal structures of materials in 3-D, and can be used to image rock samples before and after acid treatment. The geometry of wormholes generated from acid treatment together with a quantification of the resulting change in porosity can therefore be visualized in 3-D. This work presents the 3-D characterization of wormholes and the evaluation of the changes in porosity within carbonate rock samples after acid treatment using a CT technique. Possible structural and compositional controls on wormholes paths are also investigated.

SAMPLES

Four 1.5” diameter plug samples from the Swan Hills Formation in Northwestern Alberta, Western Canada Sedimentary Basin (WCSB) were selected for use in this project. The samples length ranges from about 70 – 80 mm. The mineralogy of the samples were determined semi-quantitatively using X-ray diffraction (XRD) analysis and found to be composed primarily of calcite (82 - 88 %) and dolomite (10 – 15 %) with traces of quartz and clay minerals. The samples were imaged using computed tomography before and after acid treatment in a core flood system.

ACID TREATMENT

The four plug samples were mounted in a core flood unit fitted with pressure taps. A confining pressure and a backpressure were then applied to the system until the whole system was pressurized to simulate subsurface conditions. Brine (3% KCl solution) was then injected into the core samples at a set flow rate until steady flow was achieved within the samples to measure initial permeability using Darcy’s law. Acid injection then commenced and was allowed to proceed until the pressure differential between the inlet and outlet of the core is zero indicating a wormhole breakthrough in cores. Brine was again injected continuously into the cores after the wormhole breakthrough until steady state flow was achieved to measure the final permeability of the samples using Darcy’s law again. The temperature was kept constant at 85°C throughout the experiment for all the samples. A confining pressure of 2500 psi to simulate subsurface condition and a backpressure of 500 psi to keep CO_2 (CO_2 is a reaction product during the acid treatment of carbonate rock.) in solution were chosen for all experiments. Different concentrations of hydrochloric acid (HCl) and reaction safe acid (RSA) at different flow rates due to the different initial permeability of the samples were utilized for generating varying types of wormholes.

COMPUTED TOMOGRAPHY IMAGING

Computed tomography is a non-destructive imaging technique that can be used in visualizing the internal structures of materials in 3-D. CT is based on the attenuation of X-rays passing through a material. The degree of attenuation is a function of the density of the material and the atomic numbers of the constituents of the material at a defined discrete location (voxel). As such, materials can be characterized with X-ray CT based on contrast in densities and atomic number. Since wormholes generated during acidizing represent voids, they can be distinctly extracted from CT images.

The selected plug samples were scanned using a Neurologica CereTom® NL3000 portable CT scanner. Scanning parameters were optimized for contrast and noise reduction. Each sample was scanned before and after acid treatment using a 120 kV and 7 mA tube voltage and current, respectively. The images were acquired with a resolution of 0.49 x 0.49 x 0.625 mm and reconstructed to 0.196 x 0.196 x 0.625 mm to enhance visualization.

DATA PROCESSING

Computed tomography images yield spatially resolved 3-D images of attenuation coefficients in voxel elements. These attenuation coefficients can be denoted as $\mu_{i,j,k}$ (where, i, j and k represent the spatial coordinates of voxels in a 3-D dataset) and can be represented for a voxel location as;

$$\mu_{i,j,k} = V_s\mu_{i,j,k;solid} + \varphi\mu_{i,j,k;void} \tag{1}$$

where $\mu_{i,j,k;solid}$ is the attenuation coefficient for the solid matrix components $\mu_{i,j,k;void}$ is the attenuation coefficient for the void (pore) components, V_s is the volume of the solid matrix and φ is the porosity at the voxel location ($V_s + \varphi = 1$). If a voxel location is therefore subjected to acid treatment leading to partial dissolution of the solid matrix components, the $\mu_{i,j,k}$ before (BT) and after (AT) acid treatment can be represented as follows;

$$\mu_{i,j,k\,(BT)} = V_{sBT}\mu_{i,j,k;solid} + \varphi_{BT}\mu_{i,j,k;void} \tag{2}$$

$$\mu_{i,j,k(AT)} = V_{sAT}\mu_{i,j,k;solid} + \varphi_{AT}\mu_{i,j,k;void} \tag{3}$$

Since the voids are empty, $\mu_{i,j,k;void}$ is equal to zero, therefore the change in attenuation ($\Delta\mu_{i,j,k}$) can be represented as;

$$\Delta\mu_{i,j,k} = \mu_{i,j,k\,(BT)} - \mu_{i,j,k(AT)} = (V_{sBT} - V_{sAT})\mu_{i,j,k;solid} = \Delta V_s \mu_{i,j,k;solid} \quad (4)$$

Where ΔV_s represent the change in the volume of the solid matrix after acid treatment. A resulting $\Delta\mu_{i,j,k}$ image will therefore be a mirror of the porosity image, which will illustrate the wormholes and etching generated in samples in 3-D due to acid treatment. Since acid treatment leads to the dissolution of the solid matrix, the change in porosity ($\Delta\varphi_{i,j,k}$) at every voxel location will be equal to ΔV_s and can be represented as

$$\Delta\varphi_{i,j,k} = \Delta V_s = {}^{\Delta\mu_{i,j,k}}\!/\!_{\mu_{i,j,k;solid}} \quad (5)$$

A summation of $\Delta\varphi_{i,j,k}$ from all voxel locations within samples will yield the total change in porosity of samples due to acid treatment. Determining $\Delta\mu_{i,j,k}$ values from images with confidence is highly dependent on ensuring that $\mu_{i,j,k\,(BT)}$ and $\mu_{i,j,k(AT)}$ values are from corresponding locations within the images acquired before and after acid treatment. However, accurately positioning the samples at the same i, j, k coordinate's locations before and after the acid treatment presents a challenge. It is therefore necessary to align images acquired before and after acid treatment to the same i, j, k coordinate position in space. For this purpose, a modified version of the *Manual Seed Registration* code [3], a 3D rigid body translations and rotations algorithm was employed for registering the after acid treatment images to those acquired before acid treatment. ImageJ, an open software from the National Institute of Health [4] together with customized macros were used for all image processing in this work.

RESULTS AND DISCUSSION

Analysis of CT datasets acquired before and after acid treatment in accordance with Eqn. 5 yielded the 3-D geometries of generated wormholes for the four samples investigated (Fig. 1). The samples are all characterized by the generation of a dominant wormhole that penetrates the samples from top to bottom. The wormholes are non- linear and are all characterized by complex branching networks. Etching, which is also another feature of acid treatment, is prominent on the faces of the samples on which acid injection was carried out. The etching seen around the circumferences of the four samples were created by the acid flowing towards the pressure taps installed on sample sleeves to monitor differential pressure, but have negligible impact on the measurements and interpretation.

The wormholes follow tortuous paths that vary in length and volume across the four samples. Table 1 shows some measureable attributes of the wormholes in the four samples together with the change in porosity of the samples as a result of acid treatment. It must however be understood that the computed wormhole volumes only take into account the principal axis of the dominant wormhole without the branched networks in each sample. The visualization of the distinct 3-D geometries of the wormholes together with their tortuous path lengths, volume and change in porosity improves our understanding of the effects of acid treatment on samples. These quantifiable attributes can be valuable inputs for acid stimulation programs and the validation of models.

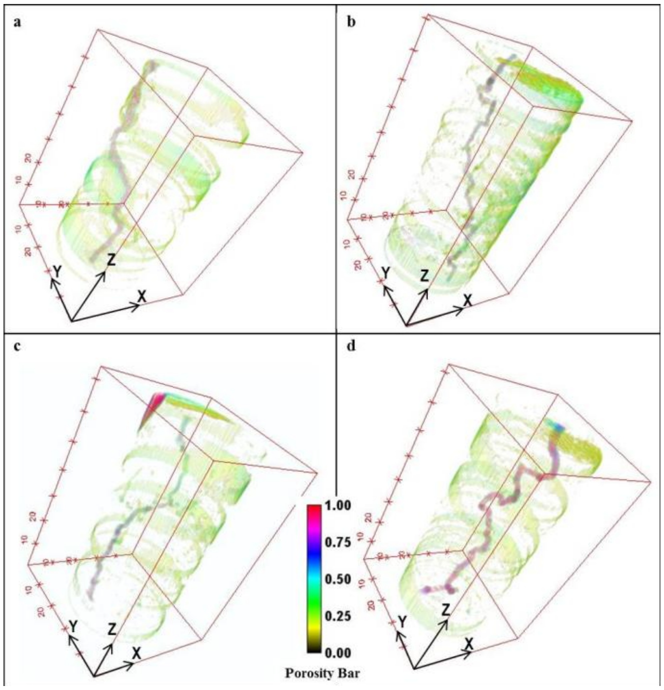

Figure 1: 3D CT showing wormhole geometry and acid etching features in 3D resulting from acid treatment of (a) Sample 1(b) Sample 2 (c) Sample 3 and (d) Sample 4.

Table 1: Summary of wormhole and sample parameters

Sample	Sample Length (mm)	WH PL (mm)	WH Volume (mm^3)	WH Tortuosity	$\Delta\varphi$ (%)	IP (mD)	FP (mD)
1	69.38	96.39	228.85	1.39	2.02	0.02	54
2	81.88	133.96	416.27	1.63	2.5	1.64	1600
3	74.38	103.17	199.3	1.39	1.71	2.52	400
4	83.13	132.45	281.19	1.59	2.75	0.91	1500

WH= wormhole, PL = Tortuous Path Length, IP = Initial Permeability, FD = Final Permeability, $\Delta\varphi$ = change in porosity

To increase our understanding of the controls on the pathways of the wormholes, we compared grayscale distributions within corresponding images acquired before and after acid treatment in all the samples. The samples are known to be predominantly made of calcite, as such, the modal grayscale value (gsv) in each sample represent the grayscale value of calcite, which was found to be approximately 3200 gsv in the four samples. It was observed that wormholes preferably followed voxel locations exhibiting grayscale values less than 3200 gsv. Voxel locations showing grayscale values lower than 3200 are either non-calcite locations or locations consisting of calcite and void. Non-calcite locations are not expected to be affected by acid treatment, as such, the wormhole pathways are assumed to be locations consisting of calcite and voids. A 2-D image along the x-z plane through the dominant wormhole in Sample 3 is shown in Figure 2 to illustrate the correlation between the wormhole pathways and voxel locations exhibiting grayscale less than 3200 gsv.

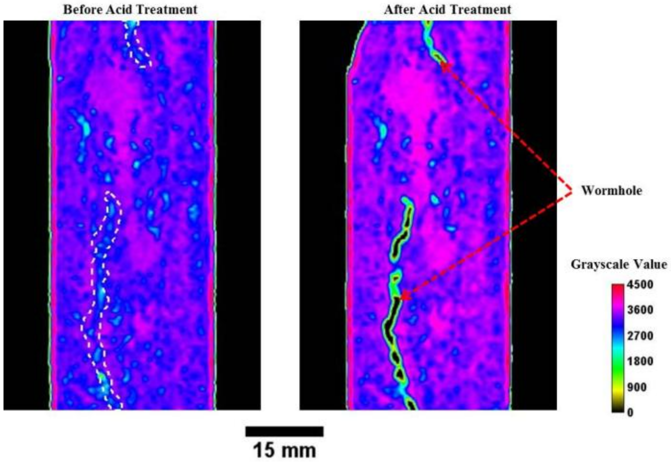

Figure 2: 2D CT images in the x-z plane illustrating of worm hole path way through locations exhibiting grayscale less than 3200 gsv representing locations made up of calcite and voids.

CONCLUSION:

We have shown the characterization of wormholes generated within carbonate samples as a result of acid treatment using computed tomography imaging technique. The wormholes are visualized in 3-D and various attributes such as tortuous path length, volume and change in porosity have been extracted by the processing of the CT images of the samples before and after acid treatment. Results provide valuable inputs in the design of acid stimulation program and can be used to verify acid stimulation models.

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