Visualizations of Berea sandstone pores using neutron tomography

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Abstract. Sandstone is a reservoir rock commonly found by oil and gas companies. Oil and gas usually trap inside the sandstone pores. A Destructive-Testing (DT) method or chemical solution method is usually used to measure the porosities of the sandstone sample. On the other hand, neutron computed tomography (NCT) can visualise and quantify all the porosities of the sandstone non-destructively. Neutron tomography is an imaging technique that employs neutron generated by a nuclear research reactor. The NCT produces cross-sectional images of the object that was used to visualise the Berea sandstone porosities distribution. The results show that each rock sample possesses connected and concentrated pores in the middle part of the rock with total porosity of ± 20%.

1. Introduction

Indonesia possesses an abundant level of minerals where oil and natural gas are the primary mineral resources. Sandstone is one of the most commonly found minerals in oil and gas companies. As oil and gas reservoir rock, sandstone possesses pores that can be filled by oil and gas. Generally, to produce a visualization of a rock, Destructive Testing (DT) is used as an option, for example, the Wood’s Metal method. Wood’s Metal is a mixed metal that commonly consists of Cadmium (Cd) and Lead (Pb) used to stick metals together. This method is utilized by injecting Wood’s Metal into the rock pores. After that, the rock is dissolved into a chemical solution which will destroy the rock and leave the hardened Wood’s Metal that shows the rock pores distribution [1]. On the other hand, by utilizing neutron tomography, the distribution of the pores can be visually produced by utilizing specific software. This method is categorized as the NDT method, where it is not necessary to destroy or dissolve the rock sample. By utilizing neutron tomography, we can also determine the value of rock porosity by using specific software [2].

Neutron radiography facility – BATAN is already enhanced for tomographic data acquisition and has been utilized to characterize and facilitate NDT on industrial materials in agriculture, medicine, archaeological geology, and building construction [3]. Neutron radiography is also used to characterize material porosity such as concretes on cultural heritage buildings. The latest utilization of neutron tomography is in the oil industry [4]. A neutron is a sub particle of an atom that possesses no charge or is neutral, not reacting with other electrical charges, and can move freely towards any other materials
until it reaches the nucleus. Because of that, neutrons are non-destructive and possess a high penetration value [5]. By utilizing neutron penetration as a radiation test, imaging is possible as a non-destructive analytical tool to determine porosity and water content in porous media, including sandstone, concrete, and so on [6]. The successful neutron penetration through the sandstone sample and the performance of special software, it is possible to predict the percentage of tar/oil/water content in the sandstone sample. Therefore, the use of Neutron Tomography as Neutron Imaging in visualizing the pores of sandstone is appropriate [7].

Unlike x-rays, neutrons interact with the nucleus of the atom, which is why they are sensitive to the different isotopes of matter. One interesting example is hydrogen (and its compounds, such as water and hydrocarbons), which weakly attenuates x-rays while being highly opaque to neutrons. Similar considerations can be made for some salts (the chlorine in NaCl is highly visible) or lithium (for battery applications). Conversely, metal such as Lead or Gold are far more transparent to neutrons than to X-rays [8].

Neutron tomography is an imaging technique that utilises neutron as its source to produce an internal structure of an object by showing the cross-sectional image of the object. Neutron tomography technique utilises neutron of a research reactor with 15MWatt thermal energy. Neutron will react on sandstone sample and form shadows on scintillator Lithium (Li). The scintillator will change neutron into blue light and then transfer it into a CCD camera. The sandstone itself is placed on a Goniometer turntable, and the image is recorded at a very turning degree. From the image, sinogram and image reconstruction are produced. Sinogram is an all-angle composition of an object projection on a single slice. Sinogram act as an input for the following process, which is the image reconstruction process [9].

The novelty of this research is that there are still few studies on the visualisation of sandstone pores using the Neutron Tomography tool for the oil and gas industry, especially in Indonesia. BATAN's nuclear reactor is the only nuclear reactor in Indonesia. Therefore, this study uses a Neutron Tomography tool that utilises neutrons from the G. A. Siwabessy Multipurpose Reactor - Serpong Nuclear Area [2]. In a previous study by Bharoto et al. [1], Limestone cores obtained directly from oil and gas reservoirs were used, while in this study, Sandstone cores in the form of Berea cores were used. Limestone has more varied materials when compared to Berea Sandstone, so Limestone has pores that are also more varied (large and small) than Berea sandstone which has almost uniform pores. Therefore, this study was conducted to visualise the pores of Berea sandstone using a Neutron Tomography tool. The reason for using this tool is because this Neutron Tomography tool uses the Non-Destructive Testing (NDT) method rather than the Destructive Testing (DT) method, which can damage the sample. This study also uses three cores instead of one to ensure the data obtained are correct.

2. Methodology

This research was conducted by utilising neutron tomography belonging to the National Nuclear Energy Agency of Indonesia (BATAN), located at G.A. Siwabessy Multi-Purpose Reactor – Serpong Nuclear Area [2]. On this neutron tomographic sandstone pore visualisation test, we utilised three sandstone samples representing three repetitions to improve data accuracy. The utilised samples are Berea Core X. Berea Cores are ideal as samples because of their average pore structure uniformity and relatively low clay content [10]. The Core X is cut into three parts and named Core X4, Core X3, and Core X7. These three cores have diameters of respectively 2.458 cm; 2.462 cm; and 2.460 cm and heights of respectively 3.747 cm; 3.793 cm; and 3.770 cm.
These core samples were then saturated with brine until their pores were filled with brine. Brine is a solution that contains sodium chloride and aquadest. After that, these three samples were tested on a neutron tomography owned by BATAN. Figure 1 shows the images of Core X4, Core X3 and Core X7.

Neutron tomography data was collected by turning the object from 0° to 360° during neutron irradiation, and the imaging data were taken at every 1° interval. Each sample projection was captured on a Charge-Coupled Device (CCD) camera and stored on a computer with LabView software's 16-bit Tagged Image File Format (TIFF). Before the tomography reconstruction, every noise on these images was removed by using image processing software called ImageJ. After that, the image reconstruction process was generated by using Octopus 8.8 software. The output of this data processing is a cross-sectional image of the object along its vertical axis. By utilising VG Studio Max 3.0 image visualisation software, the produced cross-sectional image (voxel data) was shown on a 3-dimensional image [1]. These images were analysed to obtain porosity value by using available software. The neutron tomography (RN1) image can be seen in Figure 2, and the neutron tomography scheme can be seen in Figure 3.
3. Results and discussion

The produced images through Octopus 8.8 software are sinogram images cleaned from noises and outliers using ImageJ software. These noises and outliers are unwanted because they can disrupt the primary data required in this research. Because of that, to obtain a clearer sinogram image, these noises and outliers must be eliminated. The horizontal cross-section image of Core X4, X3, and X7 was respectively taken on slices 135, 1,243, and 1,235. These three horizontal cross-sectional images can be seen in Figure 4.

As we can see in Figure 4, the black dots on the core are the core pores. Meanwhile, the white areas are core materials (matrix). Brine is a sodium chloride solution which is partially composed of water containing hydrogen atoms. The hydrogen atom greatly attenuates the thermal neutrons so that the neutrons will be absorbed in the brine and therefore appear a contrast or darker colour than the others in the image, so that it can be distinguished between the pores of the rock and the material (matrix). The same thing was also obtained by the study of Cordonnier et al. [11], where the results of Neutron Imaging using water as the material, it was found that a contrast colour (blackish grey) appeared which indicated that the neutrons were absorbed. Octopus 8.8 software was utilized, to determine the material and non-material parts of the image. Some parameters must be met to produce a decent sinogram inserted into
VG Studio Max 3.0 software. These parameters are scale, slice number, step size, central value, arctan, rotation axis, outer slice, lower limit, and upper limit. All these parameters are vital to produce clear sinogram images so that when the images are reconstructed into a 3D image, the image will be clear. After that, using VG Studio Max 3.0 software, we determined the material (matrix) and non-material (pores) of the samples and produced a 3D image that can be horizontally or vertically sliced. The horizontal slice of core X4 can be seen in Figure 5.

![Figure 5. Horizontal slice of core X4.](image1)

The same processes were also implemented on the following core, Core X3. The horizontal slice image of Core X3 can be seen in Figure 6.

![Figure 6. Horizontal slice of core X3.](image2)
Similar processes were also implemented on the following core, Core X7. The horizontal slice image of Core X7 can be seen in Figure 7.

![Figure 7. Horizontal slice of core X7.](image)

Based on the data shown on the left side of Figures 5, 6, and 7, we can see several concentrated pores in the middle of these three cores. The pores on the centre areas represent effective porosity which consists of interconnected pores only [5]. The effective porosities (interconnected pores) on these three cores are concentrated in the middle, from top to bottom. The pores in Berea sandstone are very small, so the pores outside of the connected pores are determined by the software as not core pores, which means they are "materials" and not pores. Based on the data generated by VG Studio Max 3.0 software, we determined the material and non-material volume and obtained the total porosity values of Core X4, Core X3, and Core X7, which were respectively at 20.04%; 20.11%; and 20.78%.

The results obtained for these three cores are similar because these three cores are derived from one whole core with a length of 12-inch or one foot, which is then cut into three cores (Core X4, Core X3, and Core X7) or commonly referred to as Core Plugs. Therefore, the rock characteristics of these three cores are very similar, which is indicated by the total porosity values of the three cores being almost the same.

4. Conclusion
Using the Non-Destructive Testing (NDT) method, sandstone pore visualisation analysis can be performed using Neutron Tomography by producing 2D and 3D image visualisations from Core X4, Core X3, and Core X7 samples. The core pores that are concentrated in the middle of the three cores are effective porosity. The total porosity values for Core X4, Core X3, and Core X7 are 20.04%; 20.11%; and 20.78%, respectively.

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