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Porosity Estimation from High Resolution CT SCAN Images of Rock Samples by Using Housfield Unit

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Abstract

Computer Automated Tomography has been shown to be a valuable tool in production research because it provides a non-destructive method to identify and evaluate the internal structural characteristics of reservoir rock. In CT scan, Hounsfield Unit (HU) is proportional to the degree of X-ray attenuation by the tissue. The aim of the present study was to introduce the method to estimate porosity which is one of physical parameters of reservoir rock though HU data. In this study, an Image J software was used to extract Hounsfield Unit data and calibrate by standard material's density. This method provides the ability of using CT Scanner in advanced reservoir characterization and flow test experiments.

Keywords

CT Scan, Hounsfield Unit, Porosity

1. Introduction

Computer Tomography (CT scanning) was originally developed for the medical sector (Brooks and Di Chiro, 1975; Rutherford *et al.*, 1976a; Dubal and Wiggli, 1977; Morgan, 1983) and has since found wide applications within the petroleum and other industries (Rutherford *et al.*, 1976b; Vinegar, 1986; Wellington and Vinegar, 1987). Within the petroleum industry, CT scanning technology is used to study core samples from oil and gas reservoirs, with applications in both areas of core analysis and petrophysics as well as multiphase fluid flow. CT scanners offer researchers the capability of rapid, nondestructive visualization and analysis of the internal structure of core materials and experiments involving core material [1]. CT scanners are used to provide images of sleeved and preserved core, and to identify and characterize fractures, in homogeneities, and zones of mud invasion thereby facilitating the selection of appropriate sampling intervals. Hounsfield Unit is found by Sir Godfrey Newbold Hounsfield—one of the principal engineers and developers of computed axial tomography (CAT, or CT scans).

With the powerful of this system, we decided to carry out CT scanning on 9 samples from variation wells at different basins in Vietnam such as Cuu Long basin, South Con Son basin, Song Hong basin to release the method to estimate porosity by Hounsfield units. The samples grouped as limestone, sandstone, fractured granite. These samples have Helium porosity ranges from 2.65% to 41.7%.

2. Theory and Calculation Process

As described in previous references, during the CAT scanning process the attenuation of an X-ray beam is measured as it passes through a sample material. When a parallel monochromatic X-ray beam passes through a substance of uniform density and atomic number, it is attenuated in an exponential manner such that:

$$I = I_0 * \mathrm{e}^{-\mu x}$$

where I_0 and I represent the intensity of the X-ray beam before and after passing through the substance, x is the thickness of the material and μ is defined as the linear attenuation coefficient. This formula was taken from NDT Resourse Center. Figure 1 illustrates the CT scanning process.

The linear attenuation coefficient μ is defined as the fractional decrease in X-ray intensity per unit length of that material and is a function of the atomic number and bulk density of the material and the energy of the probing X-rays. Generally, the linear attenuation coefficient is normalized to that of a standard material (such as water or air) that means each material is assigned by a unchanged number that help to calculate another material number and is defined as the Hounsfield Units (HU) or CT number of the material:

$$HU = \frac{\left(\mu_{\text{material}} - \mu_{\text{water}}\right)}{\left(\mu_{\text{water}} - \mu_{\text{air}}\right)} * 1000$$

Within a single tomographic scan, the X-ray attenuation is measured for a multitude of different angles and a cross-sectional reconstructed image is generated which represents the X-ray attenuation (CT number) in specific voxels (volume elements) of the material in a plane perpendicular to the motion of the scan (as illustrated in Figure 2). In the tomographic image light areas represent high X-ray attenuation or CT number (high density or atomic number) and darker areas represent low X-ray attenuation or CT number (low density or atomic number) [2] [3] [4].

However, the issue is how to extract the Hounsfield Units of the single cross-sectional slice. Therefore, we figure out the Image J software to solve this issue [5] [6]. Image J is a public domain Java image processing program suitable to measure distances and angles, to calculate area and pixel value statistics of user-defined selections, provide density histograms and line profile plots and so on. The measurement process will follow the flow chart in **Figure 2**.

Porosity is defined as the ratio of void volume to total volume in a soil sample. The CT scanning process provides a description of the solid and void spaces shown in cross-sections through rock samples. The steps to calculate the porosity of a rock pictured in a CT scan image are:

1) Selecting the region of interest (ROI);
2) Calibrate density;
3) Extract HU values;
4) Statistics HU values;
5) Calculate porosity.

The image processing steps were completed for this research using the Image J image analysis software, developed by the National Institutes of Health. These steps are described in detail in the following.

Selecting the region of interest removes much of "noise" and reduces "error" (isolated high intensity pixels) of digital image during CT scanning (**Figure 3**) [6] [7].

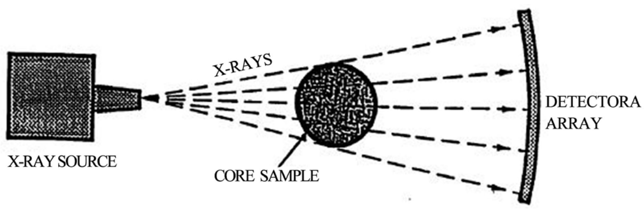


Figure 1. X-ray attenuation measurement process.

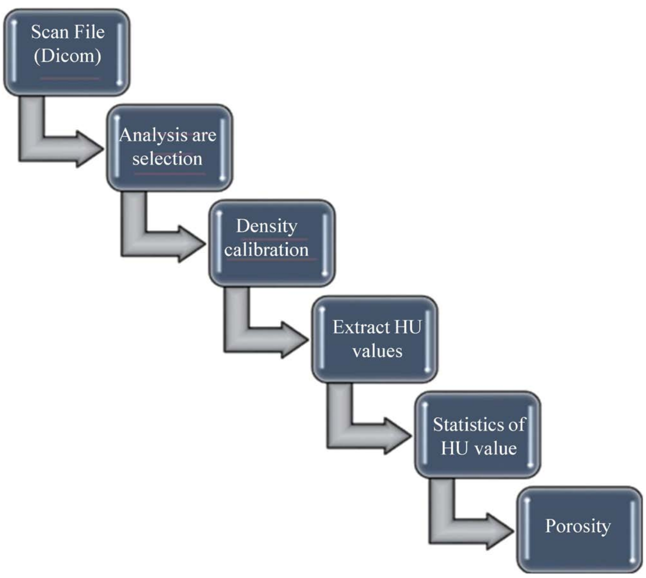


Figure 2. Measurement flow chart.

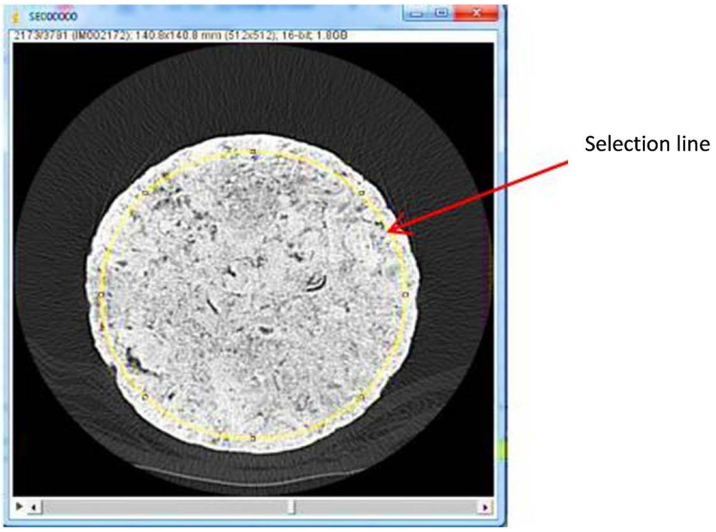


Figure 3. ROI selection of CT image.

Calibrating density is one of the most steps to create the accuracy of this method. In this part, we have to know two of material's density value which is a standard value to calibrate for all pixels in image. With each standard density, we have a correspondent Hounsfield Unit value. So that we make a trend line between HU values and density values which help to adjust the rest of pixels.

After that, we carry out HU extraction by using Image menu in the software to get HU values for each cell that intent to the table in **Figure 4**. Also we extract the histogram of ROI which let us know the max, min, mean values and total cells in our table (**Figure 5**).

With the result table we got from the software, it is easy to statistics HU values throughout the frequency of appearance and then we cumulate all of values that we received (show in **Table 1**). If total cumulative value equals total cells, we can use this statistic for porosity calculation.

Based on the table of Hounsfield Unit's common substances which applied to medical grade CT scan in **Table 2** [8] [9], we noticed the HU value of air is −1000 HU and it represent for pore value. So that, the total of cells contain value which equal or less than −1000 is pore volume, the total cells value is represent for bulk volume value.

Then, we can calculate the porosity of single slice by general equation:

$$\phi = \frac{\text{Pore volume}}{\text{bulk volume}} * 100$$

or,

$$\text{Porosity} = \frac{\text{Total cells contain HU value} \leq -1000}{\text{Total cells}} * 100$$

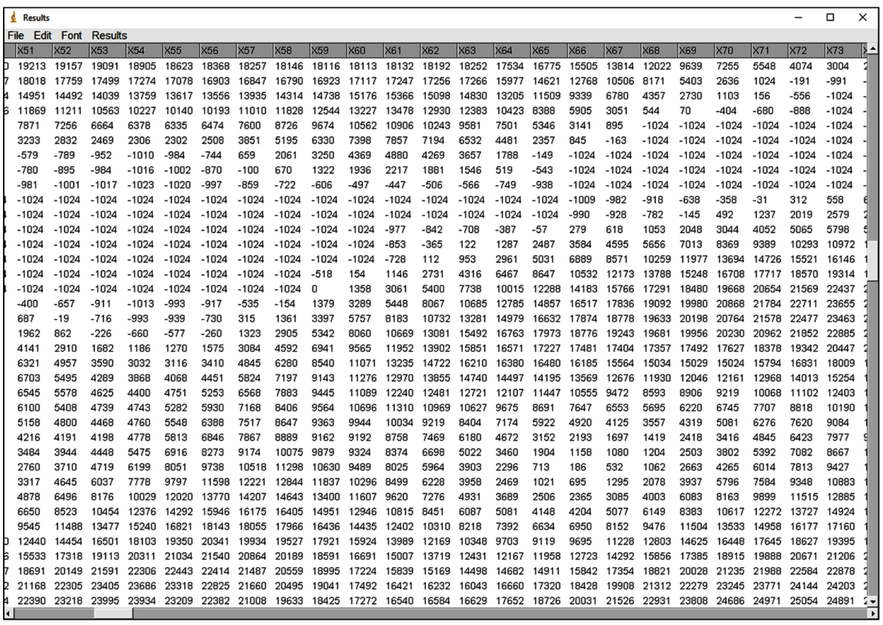
In accordance with thickness of scan system, we have the quantity of cross-sectional slices. The porosity of sample was calculated by average total porosity of all slices. Thus, the more slices we cut the more accuracy we get.

Table 1. Statistics table for single slice.

HU value	Frequency	Cummulative
−3000	7	7
−2999	8	15
…	…	…
−1001	278	5471
−1000	429	5900
−999	78	5978
…	…	…
2999	41	32,155
3000	64	32,219

Table 2. Hounsfield scale table.

Tissue	CT Number (HU)
Bone	+1000
Liver	40 - 60
Whiter mater	−20 to −30
Grey mater	−37 to −45
Blood	40
Muscle	10 - 40
Kidney	30
CSF	15
Water	0
Fat	−50 to −100
Air	−1000



X51	X52	X53	X54	X55	X56	X57	X58	X59	X60	X61	X62	X63	X64	X65	X66	X67	X68	X69	X70	X71	X72	X73
19213	19157	19091	18905	18623	18368	18257	18146	18116	18113	18132	18192	18252	17534	16775	15505	13814	12022	9639	7255	5548	4074	3004
18018	17759	17499	17274	17078	16903	16847	16790	16923	17117	17247	17256	17266	15977	14621	12768	10506	8171	5403	2636	1024	-191	-991
14951	14492	14039	13759	13617	13556	13935	14314	14738	15176	15366	15098	14830	13205	11509	9339	6780	4357	2730	1103	156	-556	-1024
11869	11211	10563	10227	10140	10193	11010	11828	12544	13227	13478	12930	12383	10423	8388	5905	3051	544	70	-404	-680	-888	-1024
7871	7256	6664	6378	6335	6474	7600	8726	9674	10562	10906	10243	9581	7501	5346	3141	895	-1024	-1024	-1024	-1024	-1024	-1024
3233	2832	2469	2306	2302	2508	3851	5195	6330	7398	7857	7194	6532	4481	2357	845	-163	-1024	-1024	-1024	-1024	-1024	-1024
-579	-789	-952	-1010	-984	-744	659	2061	3250	4369	4880	4269	3657	1788	-149	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024
-780	-895	-984	-1016	-1002	-870	-100	670	1322	1936	2217	1881	1546	519	-543	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024
-981	-1001	-1017	-1023	-1020	-997	-859	-722	-606	-497	-447	-506	-566	-749	-938	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024
-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1009	-982	-918	-638	-358	-31	312	558
-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-990	-928	-782	-145	492	1237	2019	2579
-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-977	-842	-708	-387	-57	279	618	1053	2048	3044	4052	5065	5798
-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-853	-365	122	1287	2487	3584	4595	5656	7013	8369	9389	10293	10972
-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-728	112	953	2961	5031	6889	8571	10259	11977	13694	14726	15521	16146
-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	-518	154	1146	2731	4316	6467	8647	10532	12173	13788	15248	16708	17717	18570	19314
-1024	-1024	-1024	-1024	-1024	-1024	-1024	-1024	0	1358	3061	5400	7738	10015	12288	14183	15766	17291	18480	19668	20654	21569	22437
-400	-657	-911	-1013	-993	-917	-535	-154	1379	3289	5448	8067	10685	12785	14857	16517	17836	19092	19980	20868	21784	22711	23655
687	-19	-716	-993	-939	-730	315	1361	3397	5757	8183	10732	13281	14979	16632	17874	18778	19633	20198	20764	21578	22477	23463
1962	862	-226	-660	-577	-260	1323	2905	5342	8060	10669	13081	15492	16763	17973	18776	19243	19681	19956	20230	20962	21852	22885
4141	2910	1682	1186	1270	1575	3084	4592	6941	9565	11952	13902	15851	16571	17227	17481	17404	17357	17492	17627	18378	19342	20447
6321	4957	3590	3032	3116	3410	4845	6280	8540	11071	13235	14722	16210	16380	16480	16185	15564	15034	15029	15024	15794	16831	18009
6703	5495	4289	3868	4068	4451	5824	7197	9143	11276	12970	13855	14740	14497	14195	13569	12676	11930	12046	12161	12968	14013	15254
6545	5578	4625	4400	4751	5253	6568	7883	9445	11089	12240	12481	12721	12107	11447	10555	9472	8593	8906	9219	10068	11102	12403
6100	5408	4739	4743	5282	5930	7168	8406	9564	10696	11310	10969	10627	9675	8691	7647	6553	5695	6220	6745	7707	8818	10190
5158	4800	4468	4760	5548	6388	7517	8647	9363	9944	10034	9219	8404	7174	5922	4920	4125	3557	4319	5081	6276	7620	9084
4216	4191	4198	4778	5813	6846	7867	8889	9162	9192	8758	7469	6180	4672	3152	2193	1697	1419	2418	3416	4845	6423	7977
3484	3944	4448	5475	6916	8273	9174	10075	9879	9324	8374	6698	5022	3460	1904	1158	1080	1204	2503	3802	5392	7082	8667
2760	3710	4719	6199	8051	9738	10518	11298	10630	9489	8025	5964	3903	2296	713	186	532	1062	2663	4265	6014	7813	9427
3317	4645	6037	7778	9797	11598	12221	12844	11837	10296	8499	6228	3958	2469	1021	695	1295	2078	3937	5796	7584	9348	10883
4878	6496	8176	10029	12020	13770	14207	14643	13400	11607	9620	7276	4931	3689	2506	2365	3085	4003	6083	8163	9899	11515	12885
6650	8523	10454	12376	14292	15946	16175	16405	14951	12946	10815	8451	6087	5081	4148	4204	5077	6149	8383	10617	12272	13727	14924
9545	11488	13477	15240	16821	18143	18055	17966	16436	14435	12402	10310	8218	7392	6634	6950	8152	9476	11504	13533	14958	16177	17160
12440	14454	16501	18103	19350	20341	19934	19527	17921	15924	13989	12169	10348	9703	9119	9695	11228	12803	14625	16448	17645	18627	19395
15533	17318	19113	20311	21034	21540	20864	20189	18591	16691	15007	13719	12431	12167	11958	12723	14292	15856	17385	18915	19888	20671	21206
18691	20149	21591	22306	22443	22414	21487	20559	18995	17224	15839	15169	14498	14682	14911	15842	17354	18821	20028	21235	21988	22584	22878
21168	22305	23405	23686	23318	22825	21660	20495	19041	17492	16421	16232	16043	16660	17320	18428	19908	21312	22279	23245	23771	24144	24203
22390	23218	23995	23934	23209	22382	21008	19633	18425	17272	16540	16584	16629	17652	18726	20031	21526	22931	23808	24686	24971	25054	24891

Figure 4. HU values result table.

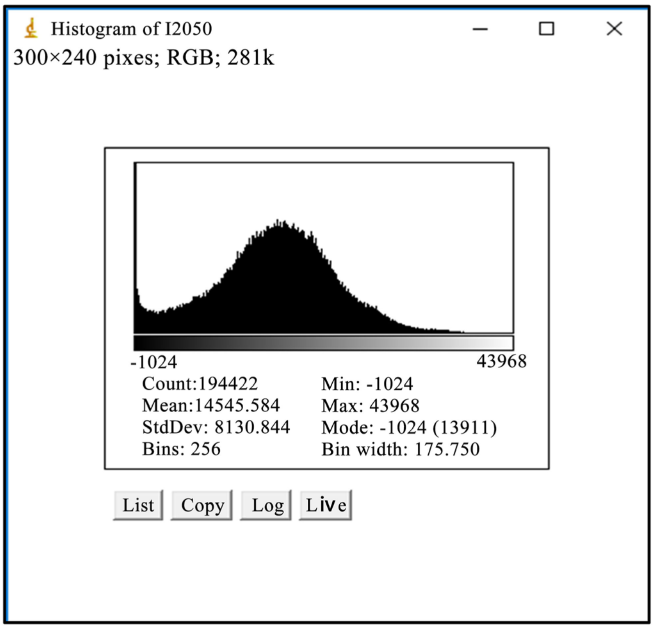


Figure 5. Histogram of HU value in ROI.

3. Results

In this research, we collect samples from wells located in Cuu Long basin, Song Hong basin, South Con Son basin and Song Hong Basin to do scan. These basins are main basins in Vietnam and located from North to South of country. The total samples we did are 9 samples where in 5 whole core samples (diameter = 4.0 inches) and 4 conventional core plugs (diameter = 1.5 inch). They were named from FD1 to FD9. The givens data was showed in **Table 3** [10].

Each sample was cut to 10 slices and calculated porosity by follow flow chart's step which describe above (**Figure 6**).

The result of each sample was showed in **Table 4**.

During calculate porosity of 9 samples by CT Scan, we also measure porosity of these samples by CMS −300 system which follow Helium injection method to verify the results from CT scanning. Finally, we have a summary table (**Table 5**).

4. Conclusion

The porosity of samples by CT Scan are quite similar with Helium porosity (connective porosity), some minority errors here should be caused by rock type especially isolate porosity in Carbonate rock (FD6).

The goal of this study was to develop non-destructive rock testing procedures using X-ray CT scanning techniques. Traditional rock testing techniques are destructive in nature and may alter the same properties they are designed to measure. Non-destructive tests provide the benefit of not altering the rock structure, so the properties of the unaltered void space may be determined without the risk of introducing systematic errors resulting from rock structure changes during the measurement process.

Table 3. Given sample data.

Sample No.	Porosity, %	Density, g/cm^3	Rock type
FD1	25.20	2.70	Carbonate
FD2	32.80	2.70	Carbonate
FD3	15.96	2.64	Sandstone
FD4	21.70	2.63	Sandstone
FD5	2.65	2.59	Granite
FD6	41.70	2.71	Carbonate
FD7	34.10	2.71	Carbonate
FD8	28.60	2.62	Sandstone
FD9	24.50	2.63	Sandstone

Table 4. Porosity (%) result table of each sample.

Slice	Sample								
	FD1	FD2	FD3	FD4	FD5	FD6	FD7	FD8	FD9
S1	31.55	31.55	19.42	18.26	3.57	54.71	33.02	24.89	21.52
S2	27.72	37.22	15.83	27.44	2.13	39.03	32.68	32.14	27.25
S3	25.11	35.11	17.25	23.10	3.01	51.91	35.18	35.92	25.16
S4	24.15	27.54	12.73	20.83	2.79	60.84	39.51	26.77	24.42
S5	23.67	28.07	20.67	23.67	1.55	37.25	41.82	19.02	23.71
S6	20.65	30.17	12.70	20.41	2.64	34.16	30.59	33.05	20.17
S7	23.61	33.72	13.16	19.52	2.88	38.93	37.24	33.84	23.46
S8	24.61	37.45	16.39	14.16	2.42	42.09	34.96	28.19	24.18
S9	26.98	36.18	18.40	22.08	3.75	37.96	33.71	26.42	26.44
S10	25.43	25.43	18.70	25.43	2.45	41.25	32.14	34.21	27.62
Average	**25.35**	**32.24**	**16.53**	**21.49**	**2.72**	**43.81**	**35.09**	**29.45**	**24.39**

Table 5. Result comparative table.

Sample No.	Porosity by CT Scan	Porosity by Helium method	Error	Rock type
FD1	25.35	25.20	**0.15**	Carbonate
FD2	32.24	32.80	**−0.56**	Carbonate
FD3	16.53	15.96	**0.57**	Sandstone
FD4	21.49	21.70	**−0.21**	Sandstone
FD5	2.72	2.65	**0.07**	Granite
FD6	43.81	41.70	**2.11**	Carbonate
FD7	35.09	34.10	**0.98**	Carbonate
FD8	29.45	28.60	**0.85**	Sandstone
FD9	24.39	24.50	**−0.11**	Sandstone

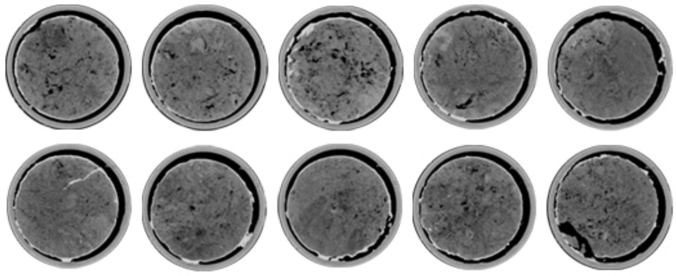


Figure 6. Illustrate 10 slices of sample FD6.

The objective of this research was also to develop image processing techniques to determine rock properties using CT scan images. The porosity results by this technique were compared with results from conventional laboratory. The accuracy of the results is proportional with quantity of slices taken for averaging, especially on heterogeneous samples. Finally, this method can be widely applied in petroleum industry.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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