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Buoyancy-dependent and Pycnometric Determination of Porosity, an Experimental Petrophysics Approach

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Abstract

This study demonstrates the determination of porosity using petrophysical laboratory approach, based on buoyancy effect, as described by the Archimedes' principle and pycnometry measurements. The objective of the study was to device an alternative method of estimating porosity robust enough for exploration and exploitation of hydrocarbon, geothermal resources, as well as for hydrogeology based on laboratory measurement, rather than spatial determination and/or simulation. In view of this, petrophysical laboratory experiment involving the use of Archimedes' and Pycnometry principles were set up, with the array of Pycnometers (Accupyc, Geopyc) and weighing balance. Two core samples, A (sandstone) and B (metamorphic) were used. The mean values of porosity were estimated using the buoyancy method in which rock masses in different media and the fluid density were substituted in an algorithm. Density and volume of the samples were calculated via pycnometry measurements, using the amount of displaced gas (Helium) in combination with Boyle's law of mass-volume relationship. While Accupyc measured matrix density, Geopyc provided both bulk masses of solid and their bulk volumes from which the porosities were estimated. The results show a porosity range from 9.9 % to 17.4 % confirming sample A to be porous sandstone. The porosity of sample B show low values ranging from 0.8% to 2.1%,

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confirming a crystalline basic rock. Considering the consistencies of the results obtained from this experiment, it follows that buoyancy and pycnometric petrophysical laboratory measurements are reliable and robust tools in estimating petrophysical parameters for rock characterization and hence, for exploration of geo-resources.

Key Words: petrophysical laboratory measurements, Porosity estimation, Rock density calculation, Rock volume calculation

1.0 Introduction

Porosity is an important petrophysical parameter of rocks amongst others (such as thermal diffusivity, conductivity, and density) in characterizing rocks for exploration of geo-resources and for many geoscientific applications. For example, in the exploration of hydrocarbon resources, the porosity of the reservoir rocks and their permeability are the most fundamental physical properties with respect to the storage and transmission of fluids. Thus, accurate knowledge of these parameters for any hydrocarbon reservoir is required for efficient development, management, and prediction of future performance of the oilfield (Korte et al., 2017). Porosity is an imperative intrinsic property of sedimentary rocks and it the dominant factor that determines the exploitable capacity of sedimentary reservoir rocks (Liang et al., 2015; Katre and Nair, 2022). Generally, heterogeneity of pore spaces is poorly represented in subsurface geological models because of the complexity factor at deeper sections of the earth, such as granular mixtures producing complex pore space controlled by grain size, grain shape, and grain sorting. Pore heterogeneity of clastic sandstone reservoirs, controlled by grain size and grain sorting, determines the volumes, flow rates, and hydrocarbons' recovery.
Defining porosity, which is the fraction of void volume over total volume, is quite simple; quantifying porosity is not as simple. This is because, the term, “void space" expressed in earth materials can span over 8 orders of magnitude in length scale, i.e., nanometer to 10s or even 100s cm or larger (Anovitz and Cole, 2015). The fact that porous rocks are the reservoirs of fossil fuels like oil and gas, as well as groundwater makes the quantification of pore spaces critical in exploration strategies (Katre and Nair, 2022). Thus, porosity must be

quantified precisely, possibly along with permeability, thermal properties, density, conductivity, diffusivity and effusivity, which are inherently related with it.

There are a large number of methods for quantifying porosity, and an increasingly complex idea of what it means to do so (Anovitz and Cole, 2015; Singh 2019; Wang et al., 2019; Saki *et al.*, 2020; Abuamarah and Nabawy, 2021; Pal, *et al.,* 2022). Most of the total porosity measurements are variations on bulk volume/grain volume or bulk density/grain density approaches, and the apparent porosity measurements were made by variations of absorption methods for different fluids or gases. For downhole petrophysical analysis based on Archie's Law provides a relationship between electrical conductivity/resistivity porosity and brine saturation, and porosity information is also provided by density, sonic and neutron logs (Peters, 2012; Tiab and Donaldson, 2012). The primary goal in pore assessment is to quantify these pores, not just in terms of shape and size, but how they contribute to the overall fabric of the rock and its ability to transmit fluids, and the bulk physical properties of the rock itself (Anovitz and Cole, 2015).

Realistic quantification of porosity is hard; making the determination of porosity is problematic (Denny, 2002; Weltje and Alberts, 2011). Porosity, as one of the main petrophysical properties of rocks, is initially controlled by environmental conditions during sediment deposition, later modified through diagenetic actions. Diagenetic processes cause rearrangement of grains and ductile grain deformation along with a change in the packing density of grains. The combined effects of primary diagenetic processes produce stable grain packing arrangements in sedimentary rocks at burial depths (Katre and Nair, 2022).

The porosity of sedimentary deposits gets considerably modified due to burial and other diagenetic processes (Worden *et al.,* 1997). Factors such as grain size and the type and stage of compaction directly affect porosity and, consequently, permeability (Lima *et al.*, 2022). Textural maturity of clastic sedimentary rocks manifests the framework grain geometry, grain shape, and grain sorting. The depositional environment's ability to modify the shape and sorting of grains decides the extent of porosity variation (Yan *et al.*, 2018; Yiming *et al.* 2019). The overall pore size and pore throats distributions control the fluid storage capacity and the ability to conduct fluid out of the pore space any geological setting and in hydrocarbon field in particular. In view of these factors, estimation and prediction of porosity, which have wide applications in environmental engineering, hydrology, hydraulic fracturing, and hydrocarbon exploration and production (Hosseini *et al.*, 2019; Ahmad *et al*., 2020; Liang *et al.,* 2021; Garia *et al,* 202; Katre and Nair, 2022,), accurate and precise analysis becomes imperative.

In this study, we demonstrate how to determine porosity based on buoyancy effect (Figure 1), as described by the Archimedes' principle and pycnometry measurement, using petrophysical laboratory approach. The objective of the study was to device an alternative method of estimating porosity robust enough for exploration and exploitation of hydrocarbon and geothermal resources, as well as for hydrogeology based on laboratory measurement, rather than spatial determination and/or simulation. In view of this, petrophysical laboratory experiment involving the use of Archimedes' and Pycnometry Principles were set up, with the array of Pycnometers (Accupyc, Geopyc) and weighing balance.

Archimedes' Principle states that 'Any object, wholly or partially immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object'. The weight of the displaced fluid is directly proportional to the volume of the displaced fluid (if the surrounding fluid is of uniform density). Thus, among completely submerged objects with equal masses, objects with greater volume have greater buoyancy.

Pycnometry principles work in general by using Pycnometers (of any type) as density measuring devices (but in fact devices for measuring volume only). Density is merely calculated as the ratio of mass to volume; mass being invariably measured on a discrete device, usually by weighing. Pycnometers are which are glass or metal containers with precisely-determined volumes, used to determine the specific gravity of sand, soil, or powdery material having granular sizes smaller than 10 mm. Pycnometers can also be used in determining the density (which is our target here) of the solid phase in a porous solid, but the sample must first be crushed, ground, or powdered to the point that all pores are opened.

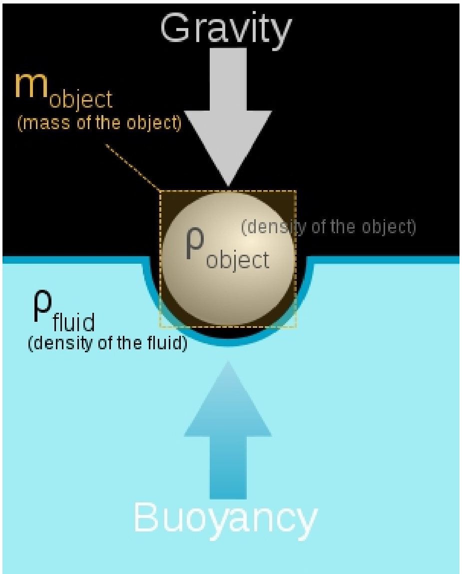

Figure 1: graphical representation of the Buoyancy and Archimedes Principle

2.0. Method

The experimental design in work is based on the Archimedes' Principle, reformulated as follows,

fluiddisplacedofwieghtweightweightimmersedApparent−= (1)

When inserted into the quotient of weights, which has been expanded by the mutual volume, we have;

$$\frac{density}{density\,of\ fluid} = \frac{weight}{weight\,of\ displaced\,fluid} \tag{2}$$

The density of the immersed object relative to the density of the fluid can easily be calculated without measuring any volumes, using;

$$\frac{density\,of\ object}{density\,of\ fluid} = \frac{weight}{weight - apparent\,immersed\,weight} \tag{3}$$

In principle, the physical parameters we are interested in measuring using these principle are porosity and density of the rock samples. While density can be calculated using equation (2), porosity can be obtained using the formulation:

$$\phi = \frac{M_{sat} - M_{dry}}{M_{sat} - M_{im}} \qquad (4)$$

Where is porosity; M_{sat} = Mass of saturated rock, M_{dry} = mass of dry sample and M_{im} mass of immersed sample.

In this work, Archimedes measurement principle entailed measuring the air- and immerged weights of the saturated halves of the two core samples of red sandstone and metamorphic conglomerate labeled A and B respectively. Each of the core samples was prepared in dry and saturated forms. Each sample was first measured on the weighing balance (to obtain the weight in air) and then suspended by some strings attached to retort stand and lowered into the bowl of water (to get the immersed weight of the sample). It was ensured that the rock sample was not resting on nor supported by the wall of the container to avoid errors in the weight reading for the samples. This procedure was followed for the saturated sample. As a way of quality control, the measurements were repeated severally to ascertain precision account for uncertainty and the values were averaged in order to obtain the final figure used in the calculation of the porosities.
Following the principles of pycnometry, the measurement of density (hence, volumes) of samples was the target. The mass of each of the samples was determined from the weight measured with the balance, from which, density was calculated. Two set of Pycnometers (AccuPyc 1340 and GeoPyc 1360) were arrayed along with a weighing balance in this experiment.

With the AccuPyc 1340 Pycnometer (Figure 2), the matrix Volume (V_{ma}) was calculated by measuring the amount of displaced gas (helium). The cutting samples of A and B again were weighed on the balance for the reading of the weights of the solid mass and then inserted into the device. This equipment had its own programme for calibration and measurement installed on a computer, enabling it to be calibrated automatically and then give the final results of the matrix densities, which were used to calculate the matrix volumes. The matrix volumes were obtained using the following empirical relationship:

$$\rho_{ma} = \frac{m}{V_{ma}} \tag{5}$$

Where *m*represents mass of the sample; *ma*ρ is the matrix density of the sample and *maV* represents the matrix volume of the sample.
Using GeoPyc 1360 Pycnometer (Figure 2), the bulk volume was determined by measuring the amount of displaced gas-medium, which were unable to enter the pores spores. Each of the cutting samples of A and B were inserted into glass cylinder-like appendages of the Geopycnometer equipment. These cylinders contain graphite powder in which the sample rotated and the measurements were taken. The final bulk volumes and the bulk densities of the rocks were measured and displayed in the raw data. The bulk volume (V_b) was obtained using the following relationship:

$$\rho_b = \frac{m}{V_b} \tag{6}$$

Where *m*represents mass of the sample; *b*ρ is the bulk density of the sample and *bV* represents the bulk volume of the sample.

Integrating the two Pycnometry results in the formulation for porosity, we have;

$$\phi = \frac{V_p}{V_b} = \frac{V_b - V_{ma}}{V_{ma} + V_p} = \frac{V_b - V_{ma}}{V_b} \tag{7}$$

Where $\rho_{ma} = \frac{M_a}{V_{ma}}$ and $\rho_b = \frac{m}{V_b}$;

and V_p = pore volume; V_b= bulk volume; V_{ma}= matrix volume; ρ_{ma}= matrix density and ϕ = porosity

Figure 2: Array of the experimental design showing the Accupyc, Geopyc and weighing balance in array

3.0 Results and Interpretation

The results of porosity using equation 4 based on the Archimedes' measurements are as shown in Table 1.

Table 1: Results of porosity estimation based on Archimedes' principle

Sample	$M_{dry}\ (g)$	$M_{sat}\ (g)$	$M_{im}\ (g)$	ϕ (%)
A	2545.4	2701.721116.529.9		
B	2174.2	2185.08798.76	0.8	

Using the equation 7, the porosity for sample A and sample B are shown in table 2. While a porosity of 17.4% was obtained from sample A, and 2.1% porosity was obtained from sample B. The porosities were determined by the combination of the data from the two types of Pycnometers used (Accupyc and Geopyc). The Accupyc gave the matrix density parameter, while the Geopyc supplied the bulk densities and volumes.

Method	Sample	$\rho_{ma}\ (g/cm^3)$	M_s (g)	$V_{ma}\ (cm^3)$	Std. Dev.	$V_b\ (cm^3)$	ϕ (%)
Accupyc	A	2.6798	35.4285	**13.2206**	0.0023	NA	17.4
	B	2.7927	17.0038	**6.0887**	0.0051		(for A)
Geopyc	A	2.2140	35.4285	NA	0.0010	**16.0020**	2.1
	B	2.7345	17.0038		0.0040	**6.2182**	(for B)

From tables 1 and 2, we see that the porosity of the A rock sample changes from 9.9% (Archimedes' method) to 17.4% (Accupyc/Geopyc methods), an increase of about 100%. First, this porosity range indicates porous sandstone. The sharp change in porosity value could be ascribed to the fact that the rock samples were cored and cut respectively from deeper and lower depths at high and lower compaction along the Stratigraphic profiles. The porosity of sample B on the other hand show a low values (0.8% in Archimedes and 2.1% in Accupyc/Geopyc methods), indicating a crystalline basic rock.

The rock bulk densities for sample A show a slight change in values between the pyconmetric tools (2.6798 g/cm3 from Accupyc and 2.2140 g/cm3 Geopyc) while those of sample B reduces slightly from 2.7927 g/cm3 (Accupyc) to 2.7345 g/cm3 (Geopyc). These differences in densities could be accounted for by the mineralogic constituents of the rocks at different depths from
where they were sampled.

The porosity mean values were estimated using the buoyancy method (dry-wet) defined by Archimedes' principle. The rock masses in different mediums (dry sample in air, saturated sample in air, saturated sample in liquid) and the fluid density were substituted in a simple algorithm from which the porosity was estimated. Density and volume of the samples were calculated using pycnometry measurements by using the amount of displaced gas (Helium) in combination with Boyle's law of mass-volume relationship. Accupyc measured bulk density, and Geopyc provided both masses of the solid and their bulk volumes from which the porosities were estimated based on simple algorithmic formulation. The raw values recorded for the Archimedes' and the Pycnometry methods are shown tables 3 and 4.

Table 3: calibrated_Bulk volume and volume report on sample A from GeoPyc 1360 V3.01; EON.ERC RWTH AACHEN Petrophysical laboratory

Devices Nr.: 292	Date: -----------
Editor: IDEA1	Time: 09:38:51

Client:RWTH	Measued density: 2.6797 g/cm^3
Sample designation: A	Sample weight: 35.4285 g
Blank measurement-Set: Intern	Blank measurement -Set: Intern
Preparation cycle 3	Measured cyce: 10
Cell diameter: 38.1000 mm	Empty Chamber:71.7788 mm
Compressional force: 90.0000 N	Conversion factor: 1.1663 cm3/mm

Nr	Initial value	Sample value	Volume (cm^3)	Deviation (cm^3)	Density (g/cm^3)	Deviation (g/cm^3)
1	11832	6646	16.0031	0.0015	2.2138	-0.0002
2	11850	6664	16.0031	0.0015	2.2138	-0.0002
3	11857	6673	15.9969	-0.0046	2.2147	0.0006
4	11869	6682	16.0062	0.0046	2.2134	-0.0006
5	11874	6687	16.0062	0.0046	2.2134	-0.0006
6	11881	6698	15.9938	-0.0077	2.2151	0.0010
7	11889	6700	16.0124	0.0108	2.2125	0.0014
8	11892	6710	15.9908	-0.0108	2.2125	-0.0014
9	11900	6712	16.0093	0.0077	2.2129	-0.0010
10	11901	6718	15.9938	-0.0077	2.2151	0.0010

Medium raw volume: 16.0016 cm^3 Standard-Deviation: 0.0073
Medium raw density: 2.2140 g/cm^3 Standard-Deviation: 0.0010
Specific Pore volume: 0.0784 cm^3/g
Porosity 17.378 %
Sample volume: 25.369 %

Table 4: calibrated Bulk volume and volume report on sample B from GeoPyc 1360 V3.01; EON.ERC RWTH AACHEN Petrophysical laboratory

Devices Nr.: 292 Date: --------------
Editor: IDEA1 Time: 10:08:56

Client: RWTH Density: 2.7927 g/cm3
Sample designation: B Sample weight: 17.0038 g
Blank measurement -Set: Intern Blank measurement -Set: Intern
Preparation cycle 3 Measured cyce: 10
Cell diameter: 38.1000 mm Empty Chamber: 71.7788 mm
Compressional force 135.0000 N Conversion factor: 2.0387 cm^3/mm
----

Nr	Initial value	Sample value	Volume (cm^3)	Deviation (cm^3)	Density (g/cm^3)	Deviation (g/cm^3)
1	11656	10504	6.2139	-0.0043	2.7363	0.0018
2	11669	10518	6.2085	-0.0097	2.7387	0.0042
3	11680	10527	6.2193	0.0010	2.7340	-0.0004
4	11688	10537	6.2085	-0.0097	2.7387	0.0042
5	11695	10540	6.2301	0.0118	2.7292	-0.0052
6	11702	10550	6.2139	-0.0043	2.7363	0.0018
7	11705	10553	6.2139	-0.0043	2.7363	0.0018
8	11710	10556	6.2247	0.0064	2.7316	-0.0028
9	11715	10563	6.2139	-0.0043	2.7363	0.0018
10	11719	10563	6.2355	0.0172	2.7269	-0.0075

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Medium raw volume: 6.2182 cm^3; Standard- Deviation: 0.0091
Medium raw density: 2.7344 g/cm^3 Standard- Deviation: 0.0040
Specific Pore volume: 0.0076 cm^3/g
Porosity: 2.084 %
Sample volume: 6.949 %

4.0 Summary and Conclusion

In this study, porosity mean values were estimated using the buoyancy method (dry-wet) defined by the Archimedes' principle. The rock masses in different mediums (dry sample in air, saturated sample in air, and saturated sample in liquid) and the fluid density were substituted in a simple algorithm from which the porosity was estimated. Density and volume of the samples were calculated through pycnometry measurements by using the amount of displaced gas (Helium) in combination with Boyle's law of mass-volume relationship. While Accupyc measured matrix density, Geopyc provided both bulk masses of solid and their bulk volumes from which the porosities were estimated based on simple algorithmic formulation.

The results show porosity of sample A, ranging from 9.9 % (Archimedes' method) to 17.4 % (Accupyc/Geopyc methods). This porosity range confirms that the sample is porous a sandstone (Sivasakthi, 2018). The sharp change in porosity value could be ascribed to the fact that the rock samples were cored and cut respectively from deeper and lower depths at high and lower compaction along the Stratigraphic profiles. The porosity of sample B shows a low values (0.8% in Archimedes and 2.1% in Accupyc/Geopyc methods), confirming a crystalline basic rock (Tullborg and Larson, 2006).

Hence, it is concluded from these experiments that porosity of rock samples can be estimated using buoyancy effects based on Archimedes' Principle and pycnometry measurements. Densities and volumes of rocks could also be calculated using the pycnometric methods. Finally, considering the consistencies of the results obtained from this experiment, it follows that buoyancy and pycnometry petrophysical laboratory measurements are reliable and robust tools in estimating petrophysical parameters for rock characterization and hence, for exploration of geo-resources.

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